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USER-EFFICIENT DESIGN:

REDUCING THE ENVIRONMENTAL IMPACT OF USER BEHAVIOUR THROUGH THE DESIGN OF PRODUCTS

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A thesis submitted for the degree of Doctor of Philosophy

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May 2011

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To mum and dad.

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Abstract

This thesis presents why a new user-centred design process for eco-design would be beneficial and demonstrates how this could be done. The research produces a methodology for collecting and measuring behaviour information and a framework for assessing its impact. It explores the role of and effective introduction of information in the design process and finally concludes with the proposed design approach for reducing the environmental impact of products during their use.

Utilising a range of qualitative and quantitative research methods, energy models, observational studies, laboratory design experiments, participation research, product prototyping and industrial consultation, a comprehensive picture of designing for energy-efficient user behaviour is formed.

It illustrates how behaviour information can be recorded and quantified, assessing the division between a product's intrinsic, technology-based, energy efficiencies and those that are deemed user-related.

Finally, in conclusion this information is then used in a new design approach which proposes a framework for the effective and time-efficient design of products, producing a prototype design which achieves an ongoing 43% energy saving in user-related losses.

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1.0 Introduction

Rising energy prices, increased energy insecurity, a growing population, a proliferation of energy-using products and an insatiable appetite for new consumer electronics are key factors steering engineers and designers worldwide to develop more energy-efficient products. This is not a new phenomenon and much work has been done to improve the technology, materials and design of products. This thesis looks at the next area of energy-efficiency improvement to be targeted, designing products so that they are not only inherently energy-efficient, using the best technology and materials, but also can only be operated and used in an energy-efficient way.

1.1 Rising Trends in Domestic Energy Use

In 2007 a report commissioned by the U.S. Consumer Electronics Association (CEA) stated that the electricity consumption of consumer electronics had grown considerably over the past ten years [CEA 2007]. It also found that predictions of energy usage in 2010 from previous studies, in 2001 by the Energy Information Administration (EIA) and in 1998 by Sanchez et al., were considered to be at least, by a factor of two, too small. The findings found that in addition to the number of installed energy-intensive appliances approximately doubling since 1997, their length of time in use had also nearly doubled. Home computer usage had increased from approximately 1,500 active hours a year, in studies from 1999 to 2004, to just less than 3,000 in 2006 [CEA 2007]. Similar rises were also seen in the use of monitors and televisions. A second U.S. report, this time in 2009 by the EIA, made predictions to 2030, showing that; with a rising average temperature, a 24% increase in the number of households and despite a continued improvement trend in energy efficiency, domestic electricity use will increase by at least 20 percent from 2007 levels [EIA 2009].

These trends of increasing domestic energy use are mirrored in the U.K. where both the ownership and energy intensity of energy-using products are on the rise [DTI 2002]. Domestic energy use has more than doubled since 1970 and by 2010 consumer electronics were predicted to be the biggest single sector of consumer electricity consumption [Energy Saving Trust, 2006]. In 2005 the Energy-using Products (EuP) Directive 2005/32/EC was passed in the European Union encouraging manufacturers to design products with the environmental impacts of the product's entire life cycle in mind. The European Commission is now able to enact product policies and implement measures on specific products and environmental aspects, such as energy consumption, waste generation, water consumption and extension of lifetime, in order to dictate a change and thus raise the environmental performance of products across the EU. This, coupled with growing environmental awareness of consumers, is causing much activity amongst product developers to focus on performance improvements and reducing energy consumption.

1.2 Energy-Efficient User Behaviour

For many energy-using domestic products, the majority of their life cycle's environmental impact is caused by the energy used during the use phase; 72% of a washing machine's life cycle impact comes from electricity use during the use phase [Electrolux 2004], 90% for a refrigerator [Rüdenauer et al. 2005] and 85% for a 32" LCD television [Schischke et al. 2008]. Therefore, any strategy which aims to reduce the overall energy impact of an energy-using product must focus on the use phase. This includes the energy efficiency of the technology used, for the products function, and the efficiency of the products use in general.

The efficiency of use is the subject of a growing body of research based on the premise that even a product designed with highly efficient technology and materials will have these benefits mitigated by "poor" user actions. If the product is misused or used unnecessarily or excessively, it will waste energy. An Australian study revealed that 15% of the electrical consumption associated with an electric kettle was unnecessary [Remmen et al. 2004]. Furthermore studies, in 1978, 1981 and 1996, from the United States, the Netherlands and the UK respectively, estimated that 26–36% of in-home energy use is due to the residents' behaviour alone [Wood et al. 2002].

Improving the energy efficiency of user habits and actions is an important new direction for product developers and government policy. Much of the work done so far to improve people's behaviour has tried to improve the effectiveness of information campaigns, providing energy feedback and improving people's awareness of the impacts of their actions. However research has shown that this information-led approach is often ineffective or produces only temporary changes to behaviour [Brandon et al. 1999, Craig et al. 1978, McKenzie-Mohr 2000]. Changing one or more of a user's beliefs, through improved information, feedback and education may not be sufficient to bring about change in the overall attitude and hence behaviour. This is best summarised by McKenzie-Mohr et al. [1999] in the following extract from his article on social marketing:

> *"[it is assumed that] changes in behaviour are brought about by increasing public knowledge regarding an issue (e.g., depletion of groundwater reserves) and by fostering attitudes that support desired activities (e.g., installing low-flow showerheads and reducing lawn watering). Consequently, designers of initiatives… attempt to alter behaviour by providing information through media advertising and by distributing brochures, flyers, and newsletters. Unfortunately, a variety of studies have established that enhanced knowledge and supportive attitudes often have little or no impact on behaviour… The failure of information intensive campaigns to foster behaviour change is due in part to their developers' underestimation of the difficulty of changing behaviour."*

Therefore, this research work is being undertaken to design the products themselves to influence or adapt to bad behaviour. Thus creating products that either force good energy-efficient behaviour or adapt to improve bad inefficient behaviour.

Changing any existing design or creating something new to accomplish this will have tradeoffs between the amount of energy saved by the new device and the amount of energy it has taken to implement. One such example from the field of domestic refrigeration is to build a refrigerator with a glass or transparent door, so that users may take their time to look and investigate what is in the refrigerator. They can then come to a decision as to what they want before opening the door and thus reduce the amount of time that they have the door open. The point here is whether the energy savings from opening the door less frequently or for a shorter period of time is compromised by the energy loss due to the reduced thermal efficiencies of the glass door. An American company has produced two identical refrigerators, one with a normal insulated door and the other with a glass door. The glass door model uses 81 kWh per year more than the standard model in the industry standard energy use test for refrigerators. This is a 17.5% increase in electricity use [Sub-Zero 2007]. Hence any improvement this design has from the improved user behaviour must make a saving of at least this percentage before any real benefit is obtained.

It is therefore necessary to be able to quantify in some way the proportion of the total energy use that is directly linked to users' behaviour before any design change can be made, and use this information at an early stage in the design process to guide and steer the design and development team.

1.3 Research Aim, Objectives and Contributions

This brief introduction has so far given an overview of the focus of the research work covered in this thesis. It argues that domestic energy use is on the rise and that the design of energy-using products can make a significant contribution to reducing this. As well as improving the base technology, materials, system and so on, the way a product is used must also be addressed. The current popular approach of pleading with users to behave in a more energy-efficient manner is insufficient. It is argued that improvements can be made through tackling these issues in the early stages of the product design process. In summary the overall aim of this research is:

To develop a user-centred engineering design process that locks energy-efficient user behaviour into the design of energy-using products.

1.3.1 Knowledge Gaps

This thesis covers two important gaps in the current research which prevent this from becoming a reality. The first is a method for quantifying the behaviour and user-related energy impacts of products, without which a design team has no focus to their work and no measure of improvement. The second investigates ways in which this information should best be used by a design team. In summary the two knowledge gaps are:

1. For the majority of consumer products there is currently no quantified data on the energy impacts of user behaviour and no established methodology for collecting such information.

2. There is no established process to enable energy use and behaviour information to be best used by the design team.

It is clear from these knowledge gaps that this thesis covers a number of different issues and thus requires a range of research methodologies to answer them sufficiently. It utilises both quantitative and qualitative methods, observational and participatory action research [Avison et al. 1999, Greenwood et al. 1993], as well as experimentation and literature studies.

The real-world application of this research necessitates a 'realist' or 'pragmatic' philosophy towards research. It thus bridges the gap between the more traditional 'positivist' and 'relativist' ends of the research spectrum forming a hybrid approach that employs a range of research methods. This will be shown in detail in chapter 3.0, but in simple terms it aims to improve the accuracy of research outcomes by having a clear goal to be investigated and understood, use triangulation and multiple methods and provide detailed written descriptions of all data collection and analysis employed [Robson 2002].

The research goal is further detailed by forming a set of four research objectives, two for the first knowledge gap and two for the second. These objectives are detailed in section 1.3.2, with a brief summary of the work that was carried out for each. Section 1.3.3 then gives an overview of the research structure, presenting research questions for each of the objectives and a detailed thesis structure shows how this work is presented (figure 1). Finally a summary of the key contributions are included in section 1.3.4.

1.3.2 Research Objectives

Four research objectives, each having several different questions and research methods, have been asked here. Included under each one is a short research description and overview of what was done:

Objective 1: ***To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour***

The causes of inefficient energy-using behaviour and reasons why it has been so difficult to reduce are discussed in detail in sections 2.1, 2.2 and 2.3 of the following literature review. This literature review covers the traditional methods for tackling behaviour-related energy use and proceeds to introduce design-led approaches to the problem and design for sustainable behaviour.

Objective 2: ***To create a way of measuring the energy impact of user's behaviour***

In order to develop any meaningful design changes the metrics, by which the users' behaviour is measured and quantified, must first be established. Chapter 4.0 presents a method for measuring the total energy impact of a product, including all intrinsic engineering and material energy inefficiencies as well as the user-related behavioural energy impact. Chapter 5.0 then details an observational study to demonstrate this methodology, gathering, measuring and presenting behavioural data.

Objective 3: ***To explore how designers might use information on behaviour to design***

In order that this large volume of data and information collected in Chapter 5.0 is best put to use, ways of using it most effectively by designers must be explored. How user-behaviour information is presented and used in the design process has been relatively under researched.

Chapter 6.0 begins with an introduction of how information is typically used by designers in the early stages of a design process. The conclusion of this is that measures of creative output from the design team could best be used to measure a performance change. Section 6.2 describes a design experiment, in which five teams of designers used information in different formats to explore the impact that the format of this user-behaviour information can have on the design process.

Objective 4: ***To investigate if it is possible to design products so that they can only be used in an energy-efficient manner***

This final objective concludes the main focus of this work: designing products so that the negative impacts of behaviour are mitigated through the design and not the attitude of the user; locking in good user behaviour for the life-time of the product.

Building on the work from question three, the behavioural data from section 5.3 is used in the development of a user-centred eco-design methodology, presented in chapter 7.0. A pilot study was first performed with the author and a single designer, in a participatory action research approach, with the conclusions and insights from this and design experiment of section 6.2 being combined into the proposed user-centred eco-design process.

The process is then tested out by the author to redesign a domestic refrigerator and generates several new design concepts, one of which is prototyped and tested in section 7.2. The results of this prototype testing show a dramatic and enduring saving of 43% in the user-related energy impact from behaviour with only simple and innovative design changes.

1.3.3 Research Structure and Methodologies

These four research objectives follow a logical construction, building on the results of one to tackle the next. Creating a complete picture of what is the impact of energy-inefficient user behaviour, how it can be measured and new products designed. These objectives have been subdivided further into specific research questions, allowing for a focused research approach and goals to be prescribed. The structure of this thesis follows in sequence and is presented in figure 1 on the following page.

At the end of each chapter, throughout this thesis, this chart of the research questions (figure 1) will be revisited and presented as a summary of the objectives and questions met and those about to be addressed. Some of the work described in this thesis is supported by additional literature and material that is described in great detail in a series of Research Appendices at the end. The reading of these appendices is not considered essential to the understanding of this thesis, but should additional references be desired, the corresponding section of these appendices is highlighted at the appropriate point in the text.

Research Questions (RQ) **Research Activity** **Chapter**

Objective 1: To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour

RQ 1.1	What is poor energy-using behaviour?	Literature Review	2.0
RQ 1.2	How can it be changed?		
RQ 1.3	Can changing behaviour be designed?		

Objective 2: To create a way of measuring the energy impact of user's behaviour

RQ 2.1	What are suitable metrics?	Energy Modelling	4.0
RQ 2.2	How significant is poor energy-using behaviour?	Use Scenarios	
RQ 2.3	How can information on behaviour be collected and turned into useful data?	Observational Studies	5.0

Objective 3: To explore how designers might use information on behaviour to design

RQ 3.1	How can this information be used to aid the design of products?	Literature Review	6.0
RQ 3.2	How do designers interact with this information?	Design Experiment	
RQ 3.3	How should this information be presented?		
RQ 3.4	What impact will it have on the design output?		

Objective 4: To investigate if it is possible to design products so that they can only be used in an energy-efficient manner

RQ 4.1	What would such a design process look like?	Participatory Research	7.0
		Design Process Demonstrator	
		Industrial Consultation	
RQ 4.2	Can a product improve the impact of poor energy-using behaviour?	Product Demonstrator	

Figure 1 - Research objectives and method proposals

1.3.4 Research Contributions

In order to set the context of the research work and to understand what the research has delivered, it is useful to summarise the outputs and the contributions to knowledge of the work. These are summarised below:

- **Guiding principles of Design for Behaviour Change**

  A review of Design for Behaviour Change and Design for Sustainable Behaviour literature, design methods and theories creates four design principles that summarise all the possible routes open to a design team. These four principles can also be arranged in a 2x2 matrix to show their relationship with the non-design methods for changing behaviour. This matrix also reveals the difference between the principles which are needed to design for existing behaviours as opposed to those which are required to create new behaviours;

- **Energy Models of User Impact - The Product Energy Profiles**

  Since quantifiable data on the energy impact of user behaviour is uncommon there is little discussion as to its size and impact relative to other forms of product energy loss. This research creates and defines three metrics (User-Related Losses, Intrinsic Losses and Theoretical Minimums) that are essential to discussions of energy efficiency of user-behaviour, presenting them into an energy model called a Product Energy Profile (PEP). Without this quantified data and modelling approach, it is impossible to judge whether an alternative design will save more energy than it costs to implement;

- **A method for collecting data on user behaviour**

  The field of eco-design has tended to rely on qualitative judgements and assessments of how users interact with products rather than measure and quantify their impacts. As a result there is a distinct lack of quantifiable data and no method for collecting it. This research reported in this thesis discusses ways in which this can be done and demonstrates it with a case study investigation of a kitchen and a domestic refrigerator;

- **Insights into the use of information in the design process**

  A design experiment is conducted which investigates various ways in which information could be presented to a design team and the different effects these have on creative output. Providing a design team with relevant and detailed information is shown to produce more effective design ideas in a given time frame. Interestingly it is also shown that stimuli information could reduce idea quantity and be a distraction to the team;

- **A practical design process for improving the energy-efficiency of user behaviour**
  Through a series of pilot design studies a design process is created, called User-Efficient Design. This design process uses information on user behaviour to design products that lock in energy efficiency of the user. The energy impact of user behaviour is reduced by 43% in a domestic refrigerator case study example;

- **Insights into the future of efficient behaviour design in industry**
  Discussions of the method and results of this design process with industry reveals barriers and obstacles to the widespread adoption of the User-Efficient Design approach. This is of great value and importance to policy makers and activists in the field of energy efficiency and eco-design as, without changes to industry standards for product testing, it is likely that the benefits of a User-Efficient Design will not translate to a product's better energy rating. This will thus reduce commercial desirability and adoption.

2.0 Literature Review and Research Direction

The focus of this research is the development of an engineering design process to reduce the amount of energy that is wasted through the inefficient use of products. Figure 2 has been created to present an overview of the research context, showing the relationships from the overarching issue at the top down to the change mechanism at the bottom. The chosen research route has also been highlighted, moving up from an engineering design solution to affect each level in turn until the key issue is met.

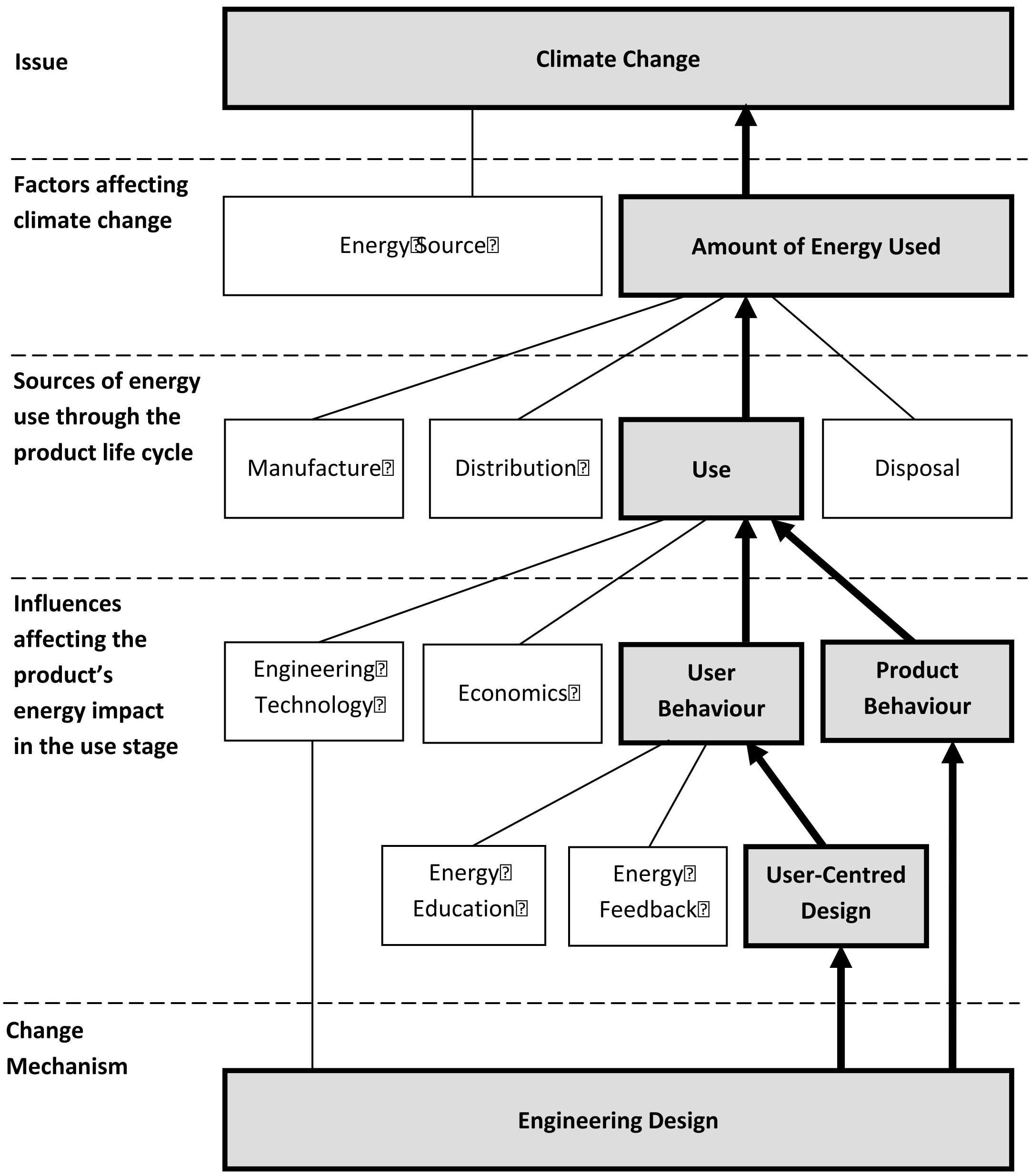


Figure 2 - Research relationship diagram showing the overview of the problem with the proposed research route highlighted

Figure 2 gives a rather simplistic but effective view of the relationships between different research fields, starting with climate change and the role of energy and the environment at the top, moving down into the life cycle analysis of products and the influences which can affect them. These influences take many different forms, from traditional measures of product efficiency in engineering technology, to human behaviour and psychology, User-Centred Design and product behaviour. All of these will be explained in much greater detail in the following sections.

It is the premise of this research that a link can be created between the engineering design of the product, the change mechanism, and its user-related efficiency. The use of User-Centred Design and design focussed on product behaviour can reduce user-related energy losses. This approach draws parallels with engineering design in the field of manufacturing changeover design, where the approach of *"doing better things rather than doing things better"* has guided machine and tooling redesign [McIntosh et al. 1996]. An engineering design approach to user-related energy efficiency has the potential to reduce energy use by making the user more aware of their impact, directly changing the user's behaviour or working independently of the user's knowledge or desire to be efficient.

This literature review has been divided broadly into three sections: Understanding Energy-Using Behaviour, Changing Energy-Using Behaviour and Designing for Behaviour Change. These three together cover all the Sources, Influences and Change Mechanism of figure 2, as well as other contextual themes such as behaviour psychology, the power of economic incentives and the other related work of researchers in this field.

2.1 Understanding Energy-Using Behaviour

"If everyone does a little, we'll achieve only a little"

– Sustainable Energy without the Hot Air [Mackay 2009]

There is a growing general public awareness of the role of energy in political and domestic affairs, from climate change and foreign policy right through to rising domestic energy prices and household bills. Domestic energy use is on the rise and people appear confused by all the energy-saving hype surrounding small mundane objects such as mobile phone chargers when the truth about effectual change is quite different. In effect, some simple strategies for minimising resource usage are futile when judged against other activities:

> *"All the energy saved in switching off a [mobile phone] charger for one day is used up in one second of car-driving. The energy saved in switching off the charger for one year is equal to the energy in a single hot bath."* [Mackay 2009]

It is widely agreed today that the energy behaviour of people in their homes has a major influence on the amount of energy used [Guerin et al. 2000]. Variations between households are considered to result from variations in micro-level activities, e.g. differences in the length of time taken to do each activity, in cooking and home laundry habits as well as in the availability of appliances. Wood et al. [2002] cite a study by Fechner from 1977 which showed that there was up to a 50% variation in electricity consumption when the consumption of six chefs was studied, all cooking the same meal with the same equipment. Furthermore they cite other studies in the United States, the Netherlands and the UK which have estimated that 26 - 36% of in home energy use is due to residents' behaviour alone.

A popular argument states that a fundamental shift in attitude and understanding, coupled with a supportive technology that lets people achieve what they want in a convenient and effective way are required to develop an energy-efficient society [Barr 2003]. These three influencers are mutually supportive and cannot be sufficient in isolation. The example of the mobile phone charger is a simple illustration of where the right attitude but an incomplete understanding has lead to people chasing insignificant energy-saving improvements. The following short extract is about a woman who had an energy-efficient attitude and knew what she wanted to do, but the technology available to her was not sufficient to achieve her goals.

> *"[An old woman was] used to keeping the lights low and dim in order to be as frugal as possible when using electricity, a habit going back to World War II. But this saving behaviour appeared to ruin the battery. To function properly, the battery needs to discharge by giving steady and strong current of electricity. The woman had unintentionally destroyed the battery. Old habits*

are very persistent and sometimes do not fit to new technologies." [Verbeek & Slob 2006]

Another factor in support of these three influencers: attitude, understanding and technology, is that of the so called rebound effect [Berkhout et al. 2000]. A classic example of the rebound effect is when consumers who had the right knowledge and technology to save energy and money, but lacked the pro-environmental attitude, switched their light bulbs to energy-efficient ones but then started using them in places that had previously not been lit, or left them on for much greater periods of time.

This is quite a common occurrence with new energy-efficient technology and the literature regarding the rebound effect state that it has direct and indirect effects. The direct rebound effects are relatively simple to understand and measure. The rebound effect states that a more efficient product will be used more often, in more places or for longer, thus reducing and possibly reversing the desired gains, as was the case with the light bulbs.

Berkhout et al. [2000] suggest that estimations for the rebound effect are typically low at between 0 - 30%, but this is speculative and can vary. A study in Kenya, improving the efficiency of wood stoves by 100 - 200%, showed rebound effects of 47 - 77% [Dimitropoulos 2007]. A rebound effect of say 10% means that 10% of the energy efficiency improvement initiated by the technological improvement has been offset by increased consumption of that same amount, a loss of potential improvement.

The indirect rebound effects are numerous, and considerably harder to mitigate, but a principal factor is that the financial savings generated by improved efficiency of energy using products would translate into a greater spending power for the consumer. Using an efficient product creates financial savings, due to a saving in fuel. This saved money is then spent on other energy-using goods or services, which could not have been purchased, had the money not been available. Pascual et al. [2006] state that "the key to a sustainable future largely depends on consumption habits and how consumers spend their money". They have addressed the issues of indirect rebound effects with eco-design strategies based on adding value to the consumer through environmental improvements, for which the consumer pays a premium, so-called Eco-Value approaches [Vogtlander et al. 2000 and Pascual et al. 2006].

Without a pro-environmental attitude, people will naturally yield to both direct and indirect rebound effects. Therefore the following chapters describe methods in which this pro-environmental attitude can be fostered and grown.

2.1.1 The Psychology of Pro-Environmental Behaviour

Trying to influence user behaviour for environmental improvement is a heavily researched and common field of work in human psychology, with many studies, over several decades, on how to influence and predict behaviour by understanding the beliefs and attitudes of the user [Kollmuss et al. 2002, McMakin et al. 2002, Bamberg et al. 2003, Guerin et al. 2000]. There have been many different models for representing the link between a person's knowledge, their attitude and their behaviour and it is beyond the scope of this section to describe them all. Instead a brief overview of the subject will be given leading to a summary of many of the barriers for adopting a pro-environmental behaviour that these models and studies have brought to light.

The early models of the link between knowledge, attitudes and pro-environmental behaviour (figure 3) were simplistic and rationalist in nature but gave an easily understood and logical framework, giving researchers and policy makers an obvious approach to follow. However, these models were soon proven to be wrong as research showed that, in most cases, increases in knowledge and awareness did not lead to pro-environmental behaviour.

Conversely, many policy makers and campaign leaders today still base their strategies on the assumption that more knowledge and information will lead to more enlightened behaviour [Kollmuss et al. 2002].

Figure 3 - Rational model of pro-environmental behaviour

Successive studies have showed this model to be flawed and highlighted the gap between attitude and behaviour. A review of several studies by Rajecki [1982] described four causes of this:

1. **Direct versus indirect experiences**

   Direct experiences of a situation, such as visiting areas of severe climate change, have a stronger effect on people's attitudes and therefore a greater influence on their behaviour than indirect experiences, for instance watching the same scenes on television;

2. **Normative influences**

   Social norms, cultural traditions and family customs influence and shape people's attitudes. Growing up in a culture of living in harmony with the environment will foster a pro-environmental attitude;

3. **Temporal discrepancy**

   Inconsistencies in results can occur when data collection for attitudes and behaviour occurs over an indiscrete period of time as people's attitudes can change over time;

4. **Attitude and behaviour measurements**

   The way the study, often a questionnaire, is worded will have a strong effect on the results and can lead to large discrepancies. For example often the questions relating to attitudes are much broader in scope such as "do you care about the environment?" than the measured actions for example "do you recycle?"

A development of this simple model (figure 3) by Fishbein and Ajzen [1975] in their Theory of Reasoned Action (figure 4) has become the most influential attitude behaviour model in social psychology and many other models have been based on it [Kollmuss et al. 2002]. To clarify some terms used, the evaluative beliefs are the person's beliefs that the behaviour leads to certain outcomes and his or her evaluations of these outcomes, whereas the normative beliefs are the person's beliefs on whether others think they should or should not perform the behaviour and thus their motivation to comply with these referents.

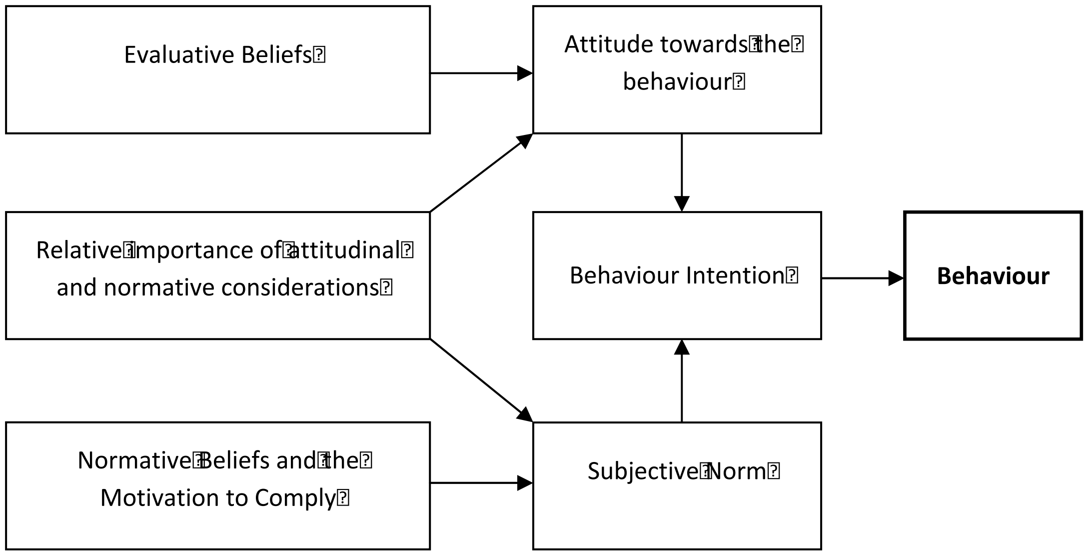


Figure 4 - Theory of Reasoned Action [Ajzen et al. 1980]

This model accounts for some of the discrepancies stated previously but maintains that human beings are rational and "make systematic use of information available to them". They are not "controlled by unconscious motives or overpowering desires", and neither is their behaviour "capricious or thoughtless" [Fishbein et al. 1975, Ajzen et al. 1980]. They argue that people consider the implications of their actions before they decide to engage or not engage in a given behaviour. A person's intention to perform any behaviour is determined by their attitude towards performing the behaviour and by their subjective norm, the person's beliefs that relevant referents think they should or should not perform the behaviour and their motivation to comply with the referents. The Theory of Reasoned Action essentially states that behavioural change is ultimately the result of changes in beliefs and social pressure, and studies have shown that this model can be used successfully to model some behaviour changes [Bamberg 2003].

However, many psychologists are contesting the idea that humans are rational, and suggest that behaviour is affected by an incalculable number of constraints, formed by a person's attitudes and beliefs. Different individuals are constrained in different ways, and changing their behaviour requires addressing the particular constraints that matter to the particular person. Some psychologists have observed that a difference in attitudes and beliefs may lead identical material conditions to have different meanings for different people. Behaviour is jointly determined by the conditions and how they are understood.

Stern [1999] developed a framework for a theory of promoting environmentally significant behaviour, dividing many of these constraints into three domains:

Personal Domain: This refers to the individual's basic values, their beliefs, the social pressures on them to behave in one way or another, their morals and social obligations. This is similar to the Theory of Reasoned Action but includes values such as curiosity, personal achievement, honesty, and obedience, to name a few.

Contextual Domain: This includes demographic attributes that individuals can often carry from birth (cultural background, religion, family economic condition and social class), acquired capabilities (education and skills), the immediate situation (economic and social), economic variables (availability of goods and services), public policy and many other factors. Generally a unique set of capabilities and constraints affects the likelihood that any particular individual will engage in any particular environmentally relevant behaviour.

Habitual Domain: Once a behaviour has been repeated often enough it can become habitual, losing a conscious connection to the personal and contextual influences on that person. The behaviour can thus be continued and repeated even if these influences change.

In 1996 Gardner and Stern wrote a book on environmental problems and human behaviour, highlighting a number of factors which can influence behaviour but also bringing to attention some problems with current psychology of behaviour change. They discuss that the choice of language is very important when phrasing questions or instructions; for example "energy conservation" is seen as a sacrifice, whereas "energy efficiency" is perhaps not. In addition showing a household how much money they are wasting by not having insulation is much more effective than saying how much money they could save. Western culture is strongly ego-centred, meaning that value and belief change does not lead to any straightforward way to behaviour change and environmental improvement, if the actions do not lead to a direct improvement in the person's personal conditions.

It is therefore important to consider that pro-environmental behaviour often brings no tangible personal benefit to those who engage in it and as a result there are considerable barriers to adopting a pro-environmental behaviour. The next section discusses these in detail and then that draws parallels with both the barriers to promoting a healthier lifestyle in medical patients and the difficulties of economists to forecast economic decisions.

2.1.2 Barriers to Adopting Pro-Environmental Behaviour

Building from the work of the previous section, numerous theoretical frameworks have been developed to explain the discrepancy between the possession of environmental knowledge and awareness with performing pro-environmental behaviour. Although numerous studies have been done, no definitive answers have been found and many studies have started suggesting barriers that prevent this from happening [Kollmuss et al. 2002]. Barriers can be:

1. **Knowledge-based,** not fully understanding or appreciating the problem;
2. **Psychological,** in terms of a perceived loss of comfort or increased sacrifice;
3. **Practical,** a lack of money or convenience;
4. **Social,** the "I will if you will" attitude.

An extensive review of many of these models and barriers by Kollmuss et al. [2002] led to the creation of their own model (figure 5) which they hoped would attempt to clarify much previous research, but with a disclaimer that developing a model which incorporates all the factors behind pro-environmental behaviour might neither be feasible nor useful. Their intention was to use it as a visual aid in clarifying and categorizing such factors.

Like many of the models, it does not attribute a direct relationship from environmental knowledge to pro-environmental behaviour but suggests environmental knowledge, values and attitudes, together with emotional involvement, as making up a 'pro-environmental consciousness'. This in turn is embedded into broader personal values and other internal as well as external factors. Social and cultural factors are put into the group of external factors but they acknowledge that it could be argued that social and cultural factors could be seen as a separate category which overlaps with internal and external factors.

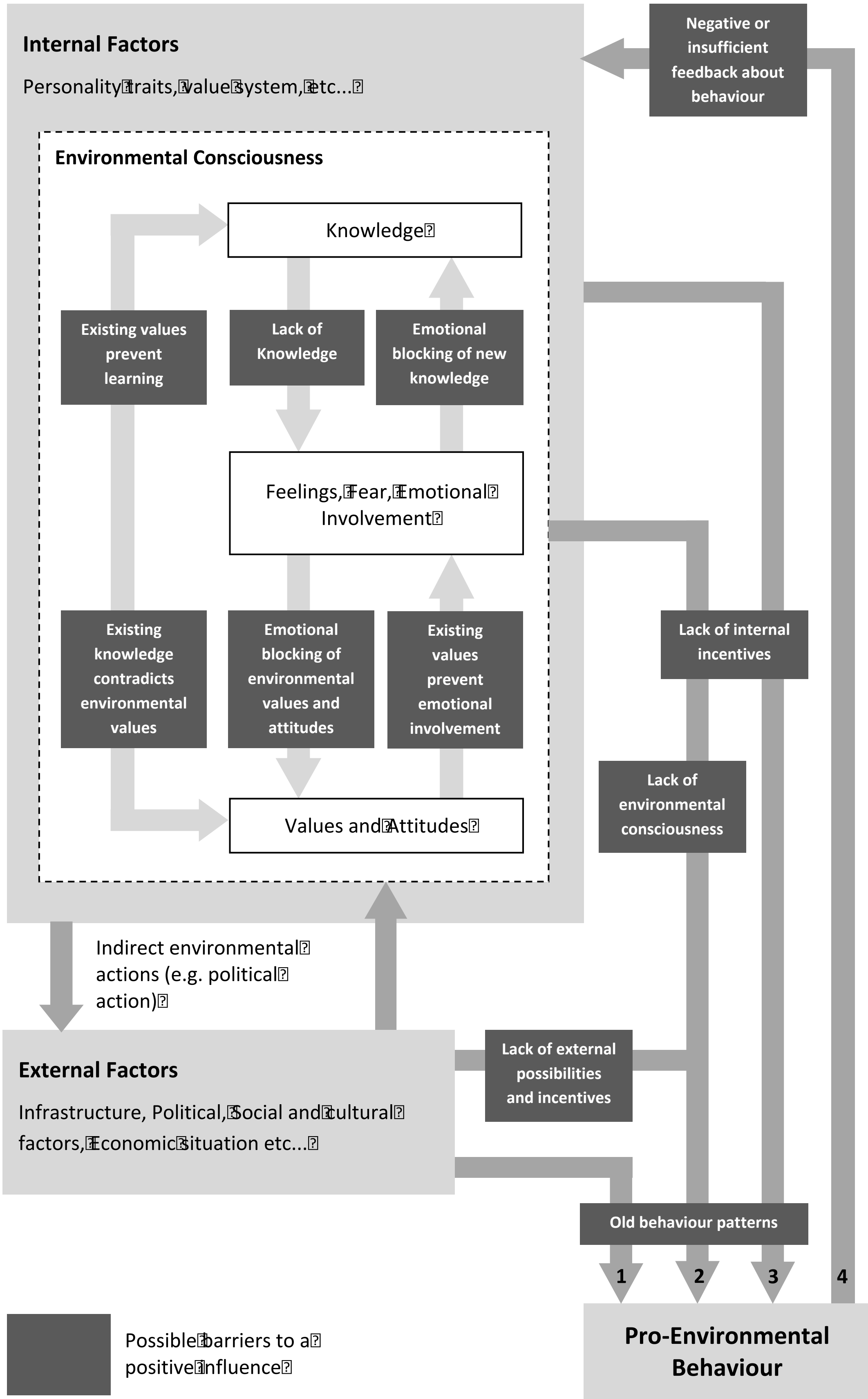


Figure 5 - Kollmuss and Agyeman's Model of Pro-Environmental Behaviour and Barriers [re-illustrated from Kollmuss et al. 2002]

The joining arrows in figure 5 indicate how the different factors influence each other and ultimately result in pro-environmental behaviour. Most are self-explanatory. The two arrows that link from internal and external factors directly to pro-environmental behaviour, arrows one and four, indicate environmental actions that are taken for reasons that are not environmentally driven. An example given is consuming less because of a value system that promotes simplicity or because of external factors such as financial constraints. The biggest positive influence on pro-environmental behaviour is achieved when internal and external factors act synergistically in arrow two. The dark boxes indicate possible barriers to positive influence on pro-environmental behaviour. The model lists only a few of the most important barriers. The largest of them is "old behaviour patterns" as old habits form a very strong barrier that is often overlooked in the literature.

Kollmuss et al.'s [2002] model is useful in presenting barriers to pro-environmental behaviour in an academic framework, but it is difficult to understand from this model how these barriers might materialise in reality. Preuss [1991 as quoted in Kollmuss et al. 2002] and Tang et al. [2008a] describe a few of the common problems people have when relating to environmental issues:

- **The intangibility of many environmental problems**

  Most environmental degradation, such as the hole in the ozone layer or the accumulation of greenhouse gases, is not immediately tangible.

- **The non-immediacy, slow and gradual ecological destruction**

  The Energy Savings Trust [2004] found that 85% of UK residents believe the effects of climate change will not be seen for decades. A poll by the BBC [2004] showed that 52% of people believe that climate change will have 'little' or 'no effect' on them personally, although it is likely these views have changed since then with the continued high-profile media coverage. Human beings are good at perceiving drastic and sudden changes but are often unable to perceive slow or incremental changes.

- **Complex systems**

  Most environmental problems are intricate and complex. People are often unable to comprehend such complex systems and tend to simplify them, for example "the issues are too large and too complex" and "consumers do not think that they can make a difference at an individual level [Jackson 2005], "I am only one person, what can I do?"

- **A lack of awareness of the link between energy use and the environment**
  Consumer understanding of the exact causes and manifestations of climate change is far too limited to make a link to their daily lives and energy use in the home [Sustainable Consumption Roundtable 2006].

- **Careless attitudes towards energy**
  86% of consumers feel guilty about the amount of energy they use [Energy Saving Trust 2006] with 42% citing laziness rather than lack of awareness as the main reason for their bad energy habits.

If people are not able to witness the effects of their actions themselves a certain amount of faith is required. This has strong parallels with attempts to promote healthy behaviour in medical patients.

2.1.3 The Parallels with Medical Patient Behaviour

In the fields of health and medicine, a positive behaviour change by a patient from an unhealthy behaviour is often the most effective prevention of illness and is essential in patient recovery. However maintaining a positive behaviour change, just as it is for environmental behaviour, is hard. Ogden et al. [2008] conducted a series of interviews with patients suffering from health related life-style behaviour issues, such as obesity and smoking, in order to try and establish what leads to a sustained behaviour change:

- The interviewees described how they had all been unsuccessful with previous attempts to change their behaviour.

- The majority described how the attempt that had been successful had been triggered by a specific life crisis, which could be interpreted as either positive or negative. As one participant remarked: "something needs to happen for you to see yourself, and then it works".

- Sustained changes often followed a reduction in choice, i.e. the perception that their choice to perform the unhealthy behaviour had been reduced. For some, this reduced choice was imposed upon them by surgery, a change in their social situation or by a shift in their life circumstances. Schwartz [2004] argued that too much choice can be overwhelming and disempowering; this reduction in choice can in fact be a liberating experience.

In summary, if patients no longer benefit from the undesirable behaviour, find that there are fewer opportunities to perform the behaviour or believe that the behaviour was the cause of their problems, then an initial change in behaviour is more likely to be translated into something long term and sustainable [Ogden et al. 2008].

The power to change behaviour by experiencing a life crisis can also be seen in studies of smoking cessation amongst doctors. Despite all having an in-depth knowledge of the relationship between smoking and lung cancer, a doctor that worked directly with patients dying of smoking-related diseases was proportionally more likely to give up than others who were shielded from the direct consequences [Goldacre 2009].

This leaves actors in the field of promoting pro-environmental behaviour with a series of challenges:

- The desired outcome is precisely to prevent the life-changing crisis, found to be so successful in health research, and so pro-environmentalists have to rely on the prophecy of disaster rather than the tangible effects.

- In the absence of personal experience of the negative consequences of their actions, it is also difficult for pro-environmentalists to build this link between the effects of behaviour and the predicted consequences.

- Finally imposing a reduction "in choice" onto people is often seen as a reduction in liberties and free-will, something that is strongly opposed to in the western world.

So how can pro-environmental and energy-efficient user behaviour be promoted? The following section explores the four main approaches adopted currently.

2.2 Changing Energy-Using Behaviour

There are many methods being used for creating more energy-efficient user behaviour [Bartiaux et al. 2006], but they can all be simplified into two motivations: fostering a 'desire to do good' and saving money'. For these there are four overarching approaches, each of which is described in turn and in detail in the following sections:

1.	**Education**	Increasing people's awareness of climate change, environmental and energy issues, and providing them with the knowledge of the consequences of their actions, so that they will want to be pro-environmental;
2.	**Feedback**	Providing people with the tools to learn which actions and behaviours are the most energy-inefficient so that they may be self-policing in their actions;
3.	**Social Marketing**	A pragmatic approach which first identifies barriers to change and then uses psychological techniques to overcome them;
4.	**Economics**	The use of financial incentives or penalties to encourage efficiency improvements and behaviour through the attraction of saving money.

2.2.1 Education

Improving education in issues relating to energy use and the environment is certainly a worthwhile focus for effort in reducing environmental impacts of people's behaviours and as a result it is probably the most pursued strategy. In 2002 a study by DEFRA (The UK Government's Department for Environment, Food and Rural Affairs) showed only 1% of the UK public had not heard of either 'climate change', 'global warming' or the 'greenhouse effect' and that most people knew the main causes and are concerned about it [DEFRA 2002]. However Gardner et al. [1996] discuss how many people do not know which of their daily actions are most responsible for energy use. Without this information, they are unlikely to act effectively on their values and beliefs, no matter how desirable. Lack of information can be a serious internal barrier to action because it is not always obvious how to act effectively.

Several studies highlight this issue, two of which are shown here to demonstrate the case. The first by Lindén et al. [2005] showed that more than 80% of surveyed households had a computer but half of the respondents did not know that it is possible to use software that sets the computer in a low-power mode after a certain time of inactivity. The second, Mansouri et al. [1996], found that there are large differences between which appliances were the most energy-intensive (table 2) and which were *perceived to be* (table 1). In their study the refrigerator and freezer were found to be the most energy intensive with energy usage ranging from 300kWh – 1700 kWh per year, with the next largest being lighting at 200 kWh – 1200 kWh. However when asking the 1,500 participating households which appliances they thought to be the largest users of electricity, the results put refrigeration in 7th place and lighting in 5th.

A raised awareness of the impacts of particular products may improve their use as people become more aware of the significance of a particular product. The appliances nominated most highly (table 1) were clothes-washing machines, electric cookers and tumble-driers. The interesting part of this study is the discrepancies between what people perceived as being high users of electricity and those which actually were (table 2). Refrigerators and freezers were not perceived as high energy users, less than 6% of the respondents ranked any of these appliances as the first or the second-highest electricity-user in their households.

Rank	*Appliance chosen as the highest electricity user in the household*	*Appliance chosen as the highest or the second-highest electricity user in the household*	*Appliance chosen as the highest or the second- or the third-highest electricity user in the household*
1	Clothes-washing machine	Clothes-washing machine	Clothes-washing machine
2	Cooker	Cooker	Cooker
3	Tumble-drier	Tumble-drier	Tumble-drier
4	Immersion heater	Dishwasher	Dishwasher
5	Lights	Immersion heater	Lights
6	Dishwasher	Lights	Immersion heater
7	Fridge-freezer	Fridge-freezer	Fridge-freezer
8	Electric fire	Electric fire	Freezer
9	Oven	Kettle	Kettle
10	Freezer	Oven	Oven
11	Kettle	Freezer	Electric fire
12	Refrigerator	Refrigerator	Refrigerator

Table 1 - Ranking of the perception of appliances by electricity consumption [Mansouri et al. 1996]

Appliance	*Average ownership level*[a]	*Annual electricity consumption for the stated appliance, if owned by a household which adopts an average usage pattern (kWh)*	*Variation in the annual electricity consumption for the stated appliance, if based on the range of usage patterns recorded in this investigation (kWh)*
Refrigeration	1.77	1020	300–1700
Dishwasher	0.43	570	360–730
Lights	1.00	440	200–1200
Electric hob	0.37	440	200–1200
Colour-television set	1.60	300	50–800
Clothes-washing machine	0.93	265	40–1300
Tumble-drier	0.53	260	50–800
Electric kettle	0.90	250	170–390
Electric oven	0.56	230	60–600
Video recorder	0.76	100	90–220
Iron	1.00	100	20–400
Microwave oven	0.74	75	40–150
Vacuum cleaner	1.00	50	30–200
Miscellaneous	1.00	360	—
Total (kWh)		4460	1610–9690

Table 2 - Ranking appliances with respect to their annual electricity consumptions in an average household and estimating the variations in consumption between households [Mansouri et al. 1996]

Mansouri et al. concludes that there is a lack of understanding among the general public as to the improvements required to reduce household energy use and cite studies that show reductions of 10 - 20% in total annual energy consumption are achievable by modifying the occupants' behaviour alone, compared with 26 - 36% from Wood et al. [2002].

A paper by Kaiser et al. [2003] discusses extensively the different forms of knowledge and how they complement each other in order to foster ecological behaviour. They discuss three kinds of knowledge:

1. **Declarative environmental knowledge,** which tends to answer questions relating to an environmental system. The paper states that the ideal is to reduce uncertainty so that people can feel confident in their actions, for example, avoiding the use of CFCs (Chlorofluorocarbons) because of knowledge of their damaging impact on the Ozone Layer;

2. **Procedural (i.e. action-related) knowledge** provides the user with ways to act or behave differently;

3. **Effectiveness knowledge,** which is particularly relevant when behaviour is trying to influence a person's cost - benefit ratio and gives knowledge on which actions are the most effective.

However, research has shown that a raising awareness of energy and environmental matters and an improvement in pro-environmental behaviour it is not a stand-alone solution as the link between the two are not consistent [Kollmuss et al. 2002, Brandon et al. 1999, Craig et al. 1978, McMakin et al. 2002, Lilley et al. 2005].

Mansouri et al. talk about how improving energy education and awareness has shown positive results but discuss how much of the energy use improvement seen in studies, where awareness was raised, could be attributed to the Hawthorne Effect. This effect describes how respondents improve temporarily because they knew they were being studied and not a genuine change in attitude [Blalock et al. 1982]. One such example would be Winnett's [1984] study showing a 10% reduction in energy-consumption after subjects had seen a 20 minute TV program about energy saving. This conclusion is supported by work from American psychologist Stern [1992] in an article entitled "What psychology knows about energy conservation".

There are a number of studies where these educational methods performed well but their results were often not sustainable, with the large initial savings reducing over time as users revert to old habits. Hayes et al. [1977] showed this with a study that they undertook on electricity use in a student housing complex, attempting to change behaviour through education. Initially, after energy efficient information was distributed, educating the user and raising energy awareness, there was a 30% reduction in usage, but in a subsequent week the savings had dropped to 9%.

The most typical result of simply presenting people with information on the benefits of pro-environmental behaviours is that the behaviour does not change. However information can be effective if it is presented when and where the target behaviour will occur and is easily validated by the target audience (see the following section on

Feedback). The most carefully crafted informational interventions have produced reductions of 10 - 20% in certain target consumer behaviours [Stern 1999].

In summary, despite the logic to providing more information and a reason why change is necessary, the results from studies do not always show that behaviour has been changed. A paper by Kaiser et al. [2003] discusses the use of knowledge and education in influencing behaviour. They state that:

> *"Our paper clarifies knowledge's significance for ecological behaviour, in spite of findings seemingly supporting the contrary. That is not to say that knowledge alone can and will reverse the ecological predicament that places human existence at risk. Other more behaviour-proximal predictors will mediate, interrupt and interfere. And powerful situational societal, political, socio-cultural and physical barriers will reduce knowledge's impact on behaviour as well. Nevertheless, knowledge remains an important and highly significant predictor of ecological behaviour."*

One way of changing behaviour, through the provision of information and increasing the education and awareness of the user, is to supply information at the time of action. This could be in the form of an energy or financial cost associated with that action and is generally known as a feedback system.

2.2.2 Feedback

If people are motivated to save energy, or to lower their energy bills, they will repeat whatever behaviours produce the reward. However it is difficult for people to tell which behaviours work as the realisation of the results may be in the future. In order to change everyday behaviour, feedback needs to be sufficiently frequent and it is probably most effective if it is available immediately before and after the time people have done something. Feedback can be either supraliminal, meaning the user is aware of the feedback, or subliminal, going unnoticed to conscious thought, both have been shown to be effective [Ham 2009].

Supraliminal feedback could be in the form of intelligent, easy to read household electricity meters that provide instant consumption readings or feedback from the product itself that instructs the user of inefficiency. An example of this, already on the market, is an alarm on a refrigerator door that sounds once it has been left open beyond a predefined time. More frequent reading and paying of domestic electricity consumption has been shown to increase user awareness and reduce consumption. Approximately 85% of electricity consumers and 90% of gas consumers in the UK (2004) pay for their energy in arrears [National Energy Action (NEA) 2006]. This is not conducive to conservation, nor to control of costs. Utilities in towns in Ontario Canada have experimented with 'pay as you go' systems successfully. The local utility Woodstock Hydro claims that, although consumers do not have a clear basis either for estimating the energy costs of appliances or for prioritising energy saving actions, if feedback of total consumption is provided centrally in the home [Wood et al. 2002], 25% of their customers who use the system would use between 15 and 20% less energy than they were doing under the traditional system of payment. This is because the display unit makes them aware of what they are consuming [Darby 2006].

However, Dennis et al. [1990] argue that feedback in the form of frequent billing or energy audits is inefficient, because consumers do not know the relative energy costs of the various energy using systems in their households. Hence, feedback should be given during, or immediately after, the use of an individual appliance. Such a system is now available in the form of Smart Meters which provide real-time energy use statistics and costs, although Weiss et al [2009] argue that this needs to be broken down to an individual product level for it to be taken up and adopted in the wider public.

The psychology viewpoint suggests that although frequent feedback works, its effect is of limited magnitude and durability because it operates mainly by promoting people to use less, rather than by encouraging people to install equipment that can give the same comfort for less. The savings from feedback will sooner or later be perceived as sacrifices [Gardner et al. 1996].

Feedback is a highly discussed and researched strategy for reducing energy consumption [Abrahamse et al. 2005, Darby 2000, Darby 2006, Dennis et al. 1990, Seligman et al. 1978]. Almost every paper which discusses energy consumption in the home considers feedback as a solution. Darby, in her paper in 2006, produces a thorough and well researched review of a great deal of feedback research. Darby distinguishes between the types of feedback available and shows the range of savings witnessed. She starts by setting the scene, saying that:

> *"Most domestic energy use, most of the time, is invisible to the user. Most people have only a vague idea of how much energy they are using for different purposes and what sort of difference they could make by changing day-to-day behaviour or investing in efficiency measures... The focus is on how people change their behaviour, not on the detail of the technology used."*

There are two types of feedback: direct, which is immediate and can monitored on an associated display monitor, and indirect, which comes from billing information, and is often delayed from the behaviour and action in question. The energy improvements associated with feedback are good but hardly warrant the amount of research and discussion. Savings from direct feedback range from 5 - 15% and the savings from indirect feedback, which is considered to be more suitable for long term energy-using systems such as space heating, is slightly less at between 0 - 10% [Darby 2006]. This is hardly the grand savings on which so much literature on user behaviour base their solution.

2.2.3 Social Marketing

Social marketing techniques have been widely used for many years in the field of public health [Kollmuss et al. 2002]. The development of social marketing specifically for sustainability arose, primarily in Canada, out of concerns about the ineffectiveness of information-led environmental campaigns.

McKenzie-Mohr et al. [1999], in their seminal book on social marketing for sustainability, state that to date most programs to foster sustainable behaviour have been information-intensive. Program planners assume that by enhancing knowledge of an issue and encouraging the development of attitudes that are supportive, behaviour will change.

Unfortunately, as previously stated a variety of studies have established that enhancing knowledge and creating supportive attitudes often has little or no impact upon behaviour and they describe the results of some studies to demonstrate this, three of which are quoted here:

- Householders who were interested in enhancing the energy efficiency of their homes participated in a comprehensive workshop on residential energy conservation. Despite significant changes in knowledge and attitudes, behaviour did not change;

- Householders who volunteered to participate in a ten-week study of water conservation received a booklet that described the relationship between water-use and energy-use and methods were described that could conserve water. It had no impact upon water consumption;

- When 500 people were interviewed regarding their personal responsibility for picking up litter, 94% acknowledged responsibility. When leaving the interview, however, only 2% picked up litter that had been "planted" by the researcher.

Social marketing emphasizes that effective program-design begins with understanding the barriers people perceive to engaging in an activity. Once the behaviours have been identified, program planners can use psychological techniques, such as commitment strategies, incentives and changing people's descriptive norms, to then go about systematically removing them.

This pragmatic approach has been offered as an alternative to conventional information campaigns and, in contrast to traditional education methods, has been shown to be very effective at bringing about behaviour change [McKenzie-Mohr et al. 1999]. A case study example of this approach in action shows an increase in domestic composting of food waste from 56% in Nova Scotia to 80% through the implementation of a number of social actions. These included the encouragement of those who already composted to speak to their neighbours who didn't and the creation of an acceptable social norm by displaying a 'We Compost' sticker on their garbage container for all to see.

McKenzie-Mohr et al. [1999] claim that the primary advantage of social marketing is that it starts with people's behaviour and works backwards to select a particular tactic suited for that behaviour.

2.2.4 Economics

The fourth theme commonly used to change behaviour relies primarily on the person's desire to save money or take advantage of financial incentives being offered. Financial incentives have been used and their effects researched for decades with an interesting mix of findings. Some of the more positive results for the use of incentives as a persuasive measure for adopting behaviour change, for example, Hutton et al. [1981] found that the use of financial incentives, specifically those that involved either a low or no cost change, significantly increased consumer responses to the energy conservation measures. Hirst [1985] also found that when a utility company offered financial incentives, this affected the user's retrofit decisions when upgrading domestic heating and cooling equipment. Lastly Guerin et al. [2000] observed that one method most frequently found to be a predictor of consumption change of an occupant's actions was their response to incentives.

However, these positive observations are not shared by all. Research by Kohn [1993] suggests that rewards and incentives succeed at securing only temporary compliance. When it comes to producing long-term and lasting changes in attitudes and behaviour, rewards, like punishments, are noticeably ineffective. Once the reward runs out, people revert to their old behaviours. Incentives, also known as extrinsic motivators, do not alter the attitudes that underlie behaviour and create no enduring commitment to any value or action. Kohn draws on studies from not only pro-environmental work but also fields of business management and health to support this, stating that incentives for losing weight, quitting smoking and using seat belts, amongst others, can not only be less effective than other strategies but often prove worse than doing nothing at all.

Titmuss [1970] claimed that monetary compensation tended to undermine an individual's sense of civic duty and responsibility. He illustrated this claim with studies from blood donations, suggesting that if donors were paid for their blood, fewer would donate. This theory gained ground over the next few years with some social psychologists calling this the "hidden costs of reward" [Lepper et al. 1978] where monetary rewards may reduce intrinsic motivation [Deci et al.1985], or Titmuss' sense of civic duty. Deci et al. went on to state that if an individual perceives an external intervention to be controlling, their intrinsic motivation to perform that task diminishes, this is now referred to as 'crowding out'. This idea of crowding out however does not mean that financial incentives can or will not work, but using incentives becomes more costly because increasing the support and subsequent response by offering greater and greater amounts must be traded off against losing support due to crowding out [Frey et al. 1997].

Frey et al. [1997] conducted a series of studies on whether people in Switzerland would be willing to accept a nuclear waste facility in their local area, with compelling results. While initially 50.8 percent of the respondents agreed to accept the nuclear waste facility without any compensation or financial incentive, the level of acceptance dropped to 24.6 percent when compensation was offered.

The design of their survey enabled them to establish this link between incentives and a loss of motivation and civic duty by eliminating some alternative reasoning. One such counter argument would suggest that the respondents were voting strategically, attempting to barter for a higher payment. A second argument would be a phenomenon known as 'signalling' where the act of offering compensation suggests subconsciously to the respondents that the facility must be more dangerous than thought. Both of these arguments were however countered by asking the respondents questions directly on these issues, to which almost no one responded favourably.

Frey et al. [1997] draw three important conclusions from their work. First, where public spirit is strong, using price incentives to muster support for the construction of a socially required but locally unwanted facility comes at a higher price than suggested by standard economic theory because these incentives tend to crowd out civic duty. Second, the use of price incentives needs to be reconsidered in all areas where intrinsic motivation can empirically be shown to be important. Finally, in areas of policy where intrinsic motivation does not exist or has already been crowded out, the use of incentives is a promising strategy to win local support.

2.2.5 Changing Energy-Using Behaviour Summary

The energy use of products is influenced heavily by the behaviour of their users [Wood et al. 2002, Mansouri et al. 1996]. There are two motivations to get people to be more energy and environmentally conscious, but the ways in which these are enacted has been shown to deliver mixed or disappointing results.

People are generally not aware of the energy impact of their own actions, or have misconceptions as to which behaviour is worse [Gardner et al. 1996, Lindén et al. 2005, Mansouri et al. 1996, Kaiser et al. 2003]. For example, 44% of the UK believes that changing their behaviour would have no effect on climate change [BBC 2004]. Therefore it is highly logical to want to raise awareness and educational standards on this issue. However research shows that despite an improved level of awareness, improvements in behaviour do not always follow [Brandon et al. 1999, Craig et al. 1978, McMakin et al. 2002, Stern 1999] or are temporary in nature [Mansouri et al. 1996, Hayes et al. 1977]. Coupling this improved knowledge and education with direct and indirect feedback methods has greater effect. It has been shown on many occasions to reduce energy consumption [Wood et al. 2003, NEA 2006, Abrahamse et al. 2005, Darby 2000 & 2006, Dennis et al. 1990, Seligman et al. 1978], with actual reduction figures of between 5% - 15% for direct and 0% - 10% for indirect feedback [Darby 2006].

On the positive side, people are more likely to make permanent changes in their energy behaviours if the new behaviours were easy and convenient to perform; when they had the skills and resources needed to change behaviours; there was a sense of competition, perhaps their neighbours and friends were also changing; and they made commitments to change in a public setting, creating a sense of peer pressure and public embarrassment if they failed [Costanzo et al. 1986, Harrigan 1991, Stern 1992]. More specifically, people are more likely to adopt energy-efficient behaviours under the following conditions:

- People view energy efficiency in terms of the benefits to themselves, especially in terms of increased thermal comfort or health, rather than as a sacrifice [Gardner 1996, Becker et al. 1981, Samuelson et al. 1991]. This is known as the "framing" of options [Lucia 2007];

- Energy use and savings are made visible with feedback systems, thus providing goals and motives where they did not previously exist [Kempton et al. 1992, Wood et al. 2002, Darby 2006];

- Information is conveyed in a vivid, salient and personal format [Costanzo et al. 1986, Dennis et al. 1990, Stern 1992], including visual modelling of specific actions to be taken [Winnett et al. 1985].

One persistent issue however with these studies, on improving behaviour, is the ever present possibility of results being distorted through Hawthorne effects [Blalock et al. 1982, Mansouri et al. 1996, Rodriguez et al. 2005], where improvements are witnessed only because the participants know they are being studied. This phenomenon is easily demonstrated by questionnaire responses. Truffer et al. [2001] found that consumers did not always purchase energy-efficient products despite their stated intentions to do so. 20% of consumers stated a willingness to pay between 10% and 20% more for energy-efficient products, yet actual adoption was less than 1%.

The final theme for this section is the use of financial incentives to persuade people to change their behaviour. Again this initially seems to be a clear indicator of action. If a person is offered a financial incentive to perform an action, it is logical to think that if this incentive were high enough to compensate for any extra effort of loss of convenience, the action would be followed.

However, research again has shown that this simple economic theory cannot fully explain user behaviour [Costanzo et al. 1986, Dennis et al. 1990, Harrigan 1991]. For example, some consumers have ignored significant financial incentives to conserve energy and others have continued to conserve even when the original financial incentive was greatly reduced [Hayes et al. 1977, Stern 1992]. In other studies, consumers were originally willing to perform an action but then were not willing to do the same action once an incentive was offered [Frey 1997, Lepper et al. 1978, Deci et al. 1985, Titmuss 1970].

In conclusion, the use of education, feedback, social marketing and economics can have a beneficial impact on energy use, but the impact may be small and susceptible to rebound effects. This is certainly disappointing due to the often considerable effort required to implement these measures. The reasons for this lack of change are varied, complex and often difficult to counter.

Many of these realisations are shared with those economists who have for a long time struggled with models of human behaviour when making financial decisions. They have traditionally based their predictions and calculations of human activity on the basis that humans are rational and behave in a way to suit their own self-interest, in much the same way as pro-environmentalists have done, through the presentation of more information, better education, improved feedback and financial incentives. As a result a new field of 'behaviour economics' [Camerer et al. 2004, Dawnay et al. 2005, Loewenstein 1999, Lucia 2007] has emerged to address this issue, creating seven guiding principles for activists and policy makers to consider when designing new measures. These are best summarised in Dawnay et al. [2005] and are listed below:

1. **People are motivated to 'do the right thing':** money can be de-motivating as it undermines people's intrinsic motivation;

2. **People's self-expectations influence how they behave:** they want their actions to support their values, beliefs and commitments;

3. **Other people's behaviour matters:** people like to copy each other and are encouraged to continue when they feel others will approve, known as Social Learning, Social Identity Theory and Social Proof;

4. **Habits are important:** even though people might want to change their behaviour, habits are hard to change, as was shown with the parallels to medical patient behaviour;

5. **People are bad at computation when making decisions:** they put undue weight on recent events and too little on far-off ones, they cannot calculate probabilities well and worry too much about unlikely events, suffering from framing and a default bias [Lucia 2007];

6. **People are loss-averse** and do not like sacrifice;

7. **People need to feel involved and effective to make a change:** giving people the incentives and information is not enough, yet too much information and choice can lead to paralysis [Lucia 2007];

So what can be done? The following section describes a design-based approach that does not necessarily require the user to have any knowledgeable input or to knowingly play an active role in changing their behaviour (in relation to energy-using products) and may eliminate all direct rebound effects. This method is designing for behaviour change.

2.3 Designing for Behaviour Change

"Speed bumps are more successful in making people drive less fast than information campaigns about the risks of driving too fast."

- Verbeek & Slob 2006

The previous section described the efforts being made to persuade the users of energy-using products to be more energy-efficient. But what if people do not care about the environment, do not believe energy use is associated with climate change, have plenty of money or are just too lazy to change their behaviour? This is a very difficult and complex issue and one where the persuasion techniques described previously would have limited impact. The alternative is designing the products themselves in such a way that they either can only be used in an energy-efficient way, coping with any bad user-behaviour and limiting negative effects. This alternative design approach is based firmly in the field of User-Centred Design (UCD) and will be introduced first in section 2.3.1 followed by a review of more specific UCD approaches that are of particular relevance to this research.

2.3.1 User-Centred Design

The essential premise of User-Centred Design (UCD) is that the best designed products will result from understanding the needs of the people who will use them. UCD is a broad term used to describe design processes in which end-users influence how a design takes shape, either through studies of them or through direct involvement in the design process. It is both a broad philosophy and a variety of methods [Abras et al. 2004]. The term originated in Donald Norman's research in the 1980s and became popular after his publication of User-Centered System Design: New Perspectives on Human-Computer Interaction [Norman et al. 1986] and his later book The Design of Everyday Things [Norman 1988].

Today UCD is common practice in many design practices with the top reasons for its adoption being: customer satisfaction, enhanced ease of use and improved sales [Vredenburg et al. 2002]. It has become so widespread, particularly in the field of HCI, that it has its own international standard: ISO DIS 13407 "Human Centred Design Processes for Interactive Systems" [Bevan et al. 1998] and has spawned many closely related design approaches within it. For example: Empathic Design [Evans et al. 2002], Pleasurable Design [Jordan 2000], Emotional Design [Norman 2004] and the newly formed

Design for Behaviour Change [Lilley et al. 2006]. It is the intention of this research to investigate whether combining the ethos of UCD with that of environmentally-conscious design, could lead to the design and production of a product whereby the most efficient way of using something is also the most intuitive [Elias et al. 2007].

At the time of writing there are a number of researchers who have been investigating this UCD approach of designing for behaviour change under a variety of different, yet highly overlapping, subject areas and titles. Figure 6 has been created to show this and listed below are a selection of lead authors and papers on each subject:

Design for Behaviour Change	Lilley et al. 2006, Elias et al. 2007, 2008a, 2008b, 2009, Rodriguez 2004, Rodriguez et al. 2005, Wever et al. 2008
Design for Sustainable Behaviour	Lilley et al. 2005, 2006, 2009, Bhamra et al. 2007, Tang et al. 2008a, 2009, Pettersen et al. 2008, Boks 2009
Scripts and Behaviour Steering	Jelsma 2000, et al. 2002, Akrich 1992, Latour 1992, 1994, Verbeek 2006, Verbeek & Slob 2006
Persuasive Technology	Fogg B.J., 1999, 2003, 2009a and 2009b, Midden et al. 2008, Consolvo et al. 2009
Design with Intent	Lockton et al. 2008a, 2008b, 2009, 2010
Design for Product Behaviour	Elias et al. 2007, 2008a, 2008b, Dewsbury et al. 2001, Orpwood et al. 2005, Stefanov et al. 2004
Design for Good Use	Rozo et al. 2009
User-Efficient Design	Elias et al. 2009a, Elias 2009b, 2010

Figure 6 shows how Design for Behaviour Change can be seen as an umbrella theme, with Design for Sustainable Behaviour as a sub-section theme within this. Many of these areas overlap between the two themes, demonstrating how a behaviour change approach could be used for environmental and sustainable purposes. These areas can also be subdivided further into methods and theories. The distinguishing element between them is that the methods describe how these themes can be applied, whereas the theories discuss the approach in general terms, without a detailed practical approach to their implementation. The following sections describe and discuss a number of the most popular methods and theories.

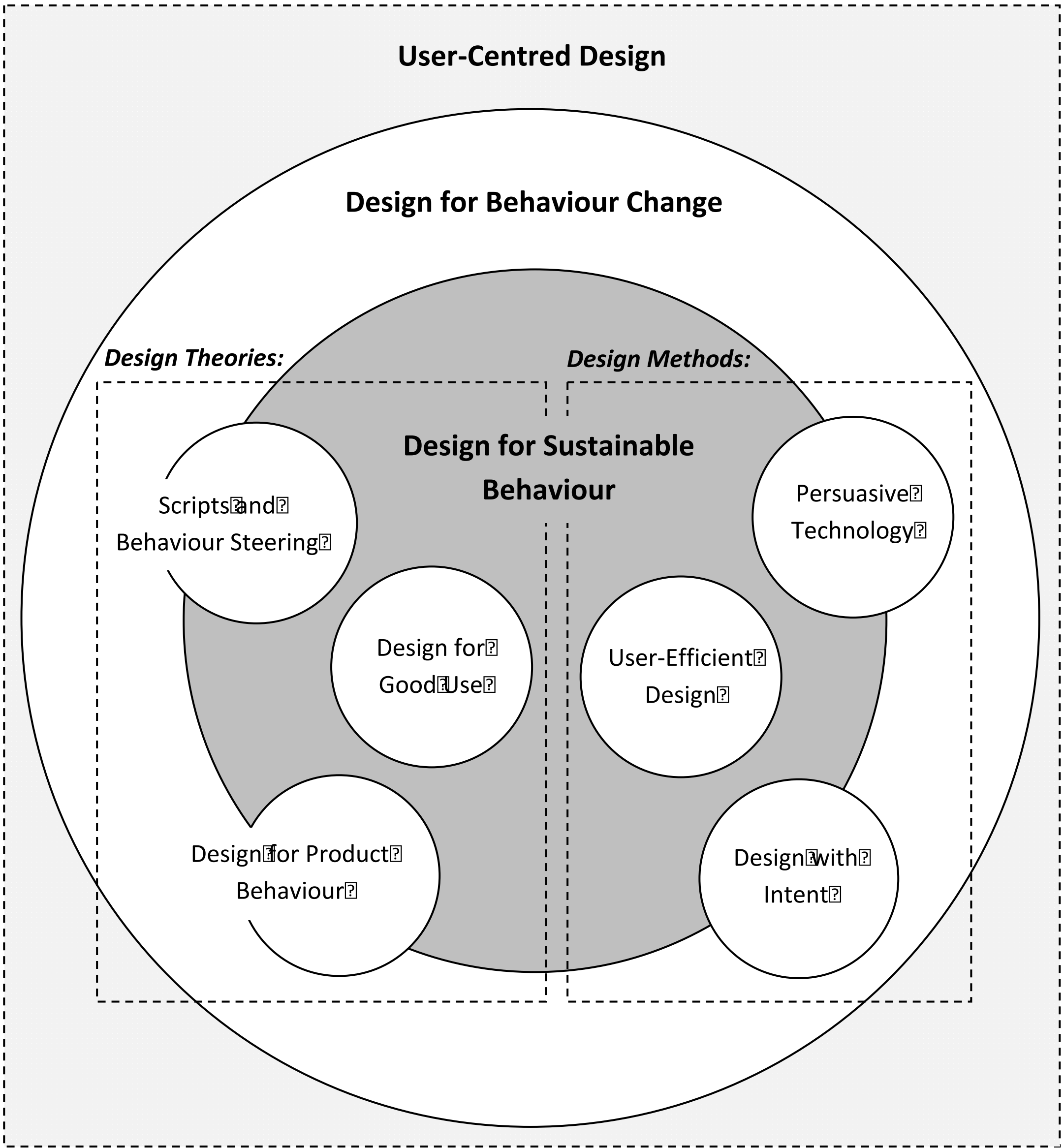


Figure 6 - Map of Overlapping Research Themes, Methods and Theories

2.3.2 Design for Sustainable Behaviour

The design stages of the product development process have a direct influence over about 70% of the final product, as this is where the most critical decisions with respect to, cost, appearance, materials selection, technical performance, environmental impact and perceptions such as quality, longevity, durability and repairability are made. Therefore designers have an unprecedented opportunity to influence the impact products can have on the environment and society in which they operate [Bhamra et al. 2007]. In November 2005, Debra Lilley, Vicky Lofthouse and Tracy Bhamra presented a paper [Lilley et al. 2005] tackling directly the issue of designing products for sustainable behaviour and highlighted some of the methods and theories:

> *"This paper reports on the findings of an eclectic literature review which draws together diverse, interdisciplinary and exploratory research in order to identify potentially viable product-led methodologies for automatically mitigating, controlling or blocking unsustainable or inappropriate behaviour by users."*

This paper has subsequently been expanded and republished in Lilley et al. 2006 and Lilley 2009. They review much of the literature relating to issues of energy efficiency and strategies for improving user-behaviour efficiency. In particular they comment that activities and research in the field of sustainable design have, to date, tended to focus on reducing the impact of manufacturing and disposal and that there appears to be a lack of consideration on the part of manufacturers and designers for the environmental effects of product use.

Lilley et al. [2005] cite that the recent drive towards sustainability has become a key policy issue at all levels of UK government. They describe three dominant strategies, favoured by government an non-government organisations to encourage users to behave in a more environmentally-friendly way, as being "linear dissemination of information", "incentives and penalties" and lastly "guilt". Although stating that there is now a growing recognition on the part of governmental agencies that "guilt" is regarded as an insufficient motivator. Subsequently policy makers have begun to realise the limitations of this approach. They summarise the findings of many researchers into a compelling case for why the provision of greater information is an ineffective strategy, stating that:

> *"A linear model of information diffusion, the one way flow….from science to policy and society is built on the assumption that provision of information will increase consumers' awareness of environmental problems and lead to positive action. The process of engagement is commonly seen in governmental*

circles as a problem of awareness and the solution lie[s] in the provision of information. Education and awareness raising through linear information diffusion has, however, consistently failed to achieve significant sustained changes in consumer behaviour."

They end their discussion on the effectiveness of educational intervention in creating sustained behavioural change by saying it is debatable, outlining many of the arguments for and against that have already been discussed in this literature review. Concluding that because so few individuals possess the insight and awareness to effectively link global issues to their own behaviour they fail to realise the critical importance of lifestyle and behavioural change. This leads users to apathy rather than action from campaigns that are focused on these macro issues.

Lilley et al. [2005] continue their literature review with a discussion of two engineering and product-led strategies for efficiency in use. The first is what they have called "technological intervention", but what this researcher calls the "intrinsic engineering technology of the product", reflecting its basis on the traditional energy efficiency approach of improving the technology and materials behind the product. An example of this would be an electronics company reducing the energy consumption of its products by using low power components, or a car manufacturer improving the fuel efficiency of its vehicles through low rolling resistance tyres.

Lilley et al. [2005] reiterate the same conclusion of this researcher that although this reduces energy use, it does nothing to prevent inefficient behaviour, making citations from rebound effect examples to support the argument. The paper therefore leads the reader into the conclusion that their final strategy, that of a product-led intervention, would be the most successful in dealing with inefficient user behaviour and they give two ways this could be done:

1. Scripts and Behaviour Steering
2. Intelligent Products and Systems

This overview work by Lilley et al. is considered very relevant to this research and so it is dealt with in more detail. The following two sections explore each of their highlighted product-led interventions in turn.

Scripts and Behaviour-Steering

Behaviour-steering technology is a term developed by Jelsma [2000] and is based heavily on the product "script" concept of Akrich [1992] and Latour [1992] who challenged the strictly functional vision of technology. They introduce the concept that products and technologies possess a "script" in the sense that they can prescribe the actions of the actors involved [Akrich 1992, Latour 1992, Jelsma et al. 2002, Verbeek & Slob 2006].

Products can evoke certain kinds of behaviour: a speed bump invites drivers to slow down because of the discomfort caused and its ability to damage a car's shock absorbers, a car can demand from a driver that he or she wear the safety belt by refusing to start if the belt is not used and a plastic coffee cup has the script "throw me away after use," whereas a porcelain cup "asks" to be cleaned and used again. Technological artefacts can influence human behaviour and this influence can be understood in terms of scripts. Designers will naturally anticipate how users interact with the product they are designing and, implicitly or explicitly, build prescriptions and defaults for use into the materiality of the product [Kesan 2006].

This theory of product scripts is essentially a development of Gibson and Norman's theory of affordances [Gibson 1979 and Norman 1988] which explores the users' perceptions of the affordances a product or environment makes available to them. An example of the power of perceived product affordances is the use of handles or plates on doors to signal whether the door should be pulled or pushed. This can often lead to frustration and confusion when a door whose handle appears to say "pull me" actually requires the door to be pushed.

Norman [1988] also describes some other behaviour-steering constraints, including forcing functions such as interlocks, where behaviours and actions have precedence over one another and one condition must be satisfied before the next can start or function enabled. This kind of interlock system is common in manufacturing [Shingo 1986] and machine-design health and safety.

Although this researcher agrees the use of scripts can be a method for guiding behaviour, much of their impact is dependent on the attitude, education and beliefs of the user and so considers them to be less effective than other design-led interventions. An example often given for a scripted design is that of a plastic coffee cup, which compared to a china mug, embodies the script of "throw me away after use". This embodied script only exists within a particular mental framework. For example a jungle tribesman may see this object with a very different script, or the driver of an all-terrain vehicle may see the script of a road speed bump in a different way to the driver of a lowered sports car. Finally an example which neatly demonstrates this is from China, as quoted from Kollmuss et al. [2002], where local people travelling in trains were used to:

> *"Disposing of their food and drinking utensils by throwing them out of the window. Formerly, this habit made perfect sense, since the drinking cups and the packaging were out of clay and other organic materials. More recently, these have been replaced by styrofoam and plastics. China now has a serious littering problem because people are still disposing of these new, non-degradable materials in the same way."*

As such, this script approach relies on the personal, contextual and habitual domains of Stern [1999] and which, having been discussed earlier, cannot be relied upon as a design-led intervention. What is required is a stronger intervention that not only prompts a script of user behaviour but prevents unacceptable behaviours. Lilley et al.'s second highlighted product-led strategy will do just that.

Intelligent Products and Systems

The concept of intelligent products and systems matches very closely with the research focus of this thesis. Lilley et al. give a good example of a Honda engine which automatically turns itself off and on at traffic lights to save energy and reduce emissions. The drivers are not aware of the actions taken, nor are they consciously choosing the behaviour.

They then present a model for product-led interventions (figure 7) which gives a good overview of the relationships between product, user and behaviour. The model presents many factors which a designer should consider, including positive and negative local, national and global factors which may affect the user. The user's relationship with the product can then be divided into positive behaviours which should be encouraged and negative ones which should be addressed. Product "Disablers" and "Enablers" can then be used to change the behaviour accordingly.

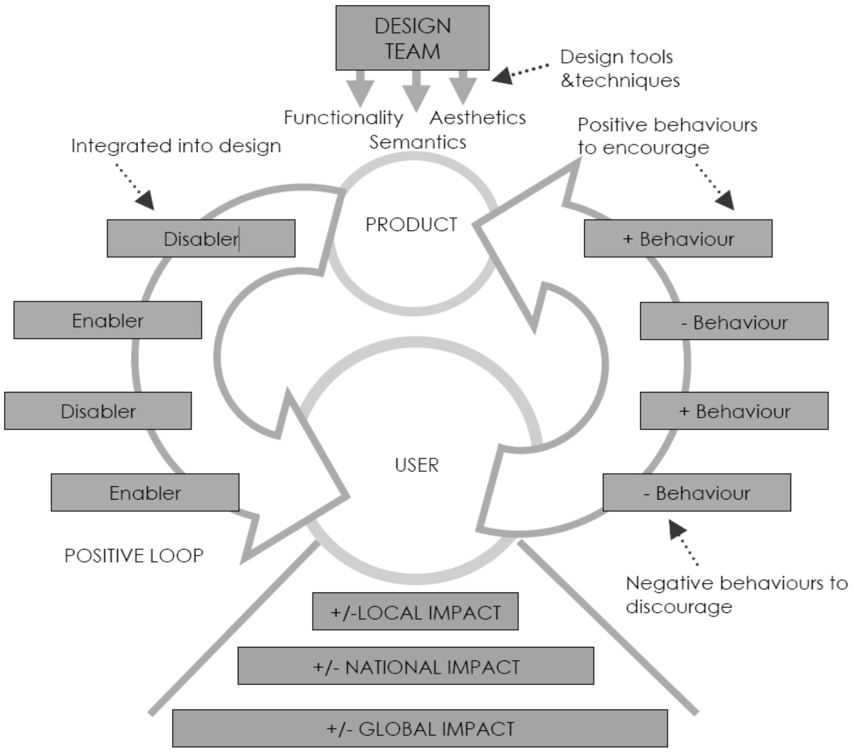


Figure 7 - Product Intervention Model [Lilley et al. 2005]

Overall, this is an important paper on the subject and has greatly assisted the dissemination of information on designing for sustainable behaviour. However it does not present a sufficiently detailed design methodology or tool for its implementation. In all three versions of the paper [2005, 2006 and 2009] the authors discuss the example of redesigning a mobile phone so that it is used in a more "polite manner".

This example is well presented and demonstrates the concept of designing for a behaviour change, but in order for their approach to be used for energy, rather than social, improvements, it perhaps lacks the rigour of using quantifiable data and metrics for measuring improvement. The practical application of designing a product for sustainable energy-efficient behaviour is an obvious gap in the research knowledge.

Developments in Design for Sustainable Behaviour

In 2008 Tang and Bhamra took a fresh look at the earlier work of Lilley, Lofthouse and Bhamra on this subject. They address this lack of practical application by producing a paper detailing seven design-led approaches available to a designer. Their interventions are listed below and arranged into a graph of varying emphasis (figure 8):

1. **Eco-Information:** Makes energy consumables visible, understandable and accessible;
2. **Eco-Choice:** Encourages consumers to think about their behaviour and take responsibility for their actions;
3. **Eco-Feedback:** Facilitates behaviour change by offering real-time feedback
4. **Eco-Spur:** Rewards good usage and punishes unsustainable behaviour;
5. **Eco-Steer:** Builds prescriptions, scripts and constraints into the product;
6. **Eco-Technology:** Restrains existing use and persuades or controls behaviour automatically through product design;
7. **Clever Design:** Automatically acts in a sustainable way without changing behaviour, through purely product design.

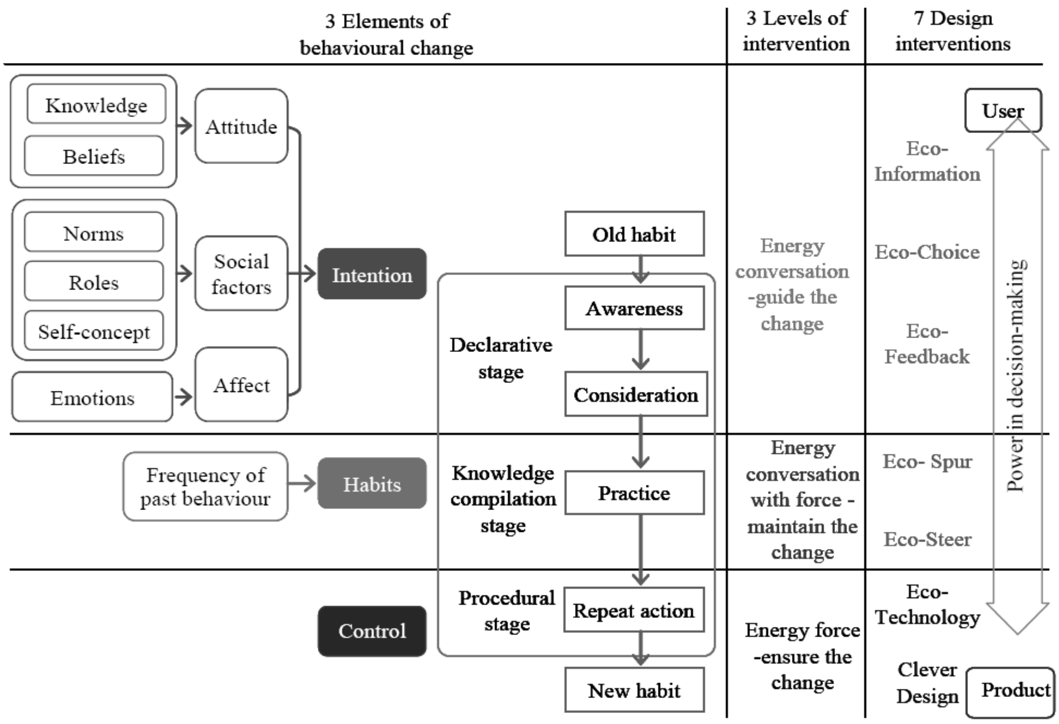


Figure 8 - Seven Design Interventions [Tang et al. 2008a]

Tang et al. [2008a] try to unify much of the work in this field into a single framework (figure 8). To support this they cite specific product designs that meet each of their seven interventions. Furthermore they link them with the psychological literature on behaviour change in the proposed "three elements of behavioural change" and "three levels of intervention".

This is another valuable contribution although some clarity is needed in the language used to describe the seven interventions as it can be difficult to distinguish between them.

2.3.3 Persuasive Technology

Persuasive technology and captology is the use and design of computers and computer interfaces as a persuasive technology to guide and encourage particular behaviours. As a discipline this has been thoroughly developed by B. J. Fogg since the late 1990s [Fogg 1999, 2003, 2009a and 2009b]. Fogg's work is based primarily in the context of website and computer software design and so there is significant potential to use this for improving the environmental impact of computers and their associate products such as printers. Researchers in the design for behaviour change also believe that many of the techniques and tools used in persuasive technology could be applied to a wider eco-design field [Lockton 2008a, Midden 2008].

Fogg [2009b] comments that, in today's world, persuasive technologies are commonplace and ubiquitous, being surrounded by digital products designed to change what people think and do. Persuasive technology experiences can come from: the internet, video games, mobile phones and even specialized consumer electronic devices, such as bathroom scales that track body mass. In this paper, Fogg goes on to suggest that the lack of a well-defined process for designing persuasive technology requires people to adapt methods from other fields, such as usability engineering, or to make guesses as how to define and develop their products. He argues that neither approach is efficient as attempts to create persuasive technologies often fail.

As a result he has attempted to provide an eight-step best practice for developing new persuasive technologies (figure 9). He also states that the most common problem many persuasive technology projects have is that they are too ambitious.

Step 1 - Choose a simple behaviour to target

The first step is the most important aspect of designing successful persuasive technologies: to select an appropriate behaviour to target for change. The design team should select the smallest, simplest behaviour that matters. Often this requires a team to reduce their overall goal to a smaller objective, which, if successful, could be scaled up. If the overall goal is to get people to be pro-environmental, the small objective of motivating them to change a single light bulb in their home could alter how they view themselves. Over time it is argued they will now be more likely to make other pro-environmental choices that are consistent with this small objective.

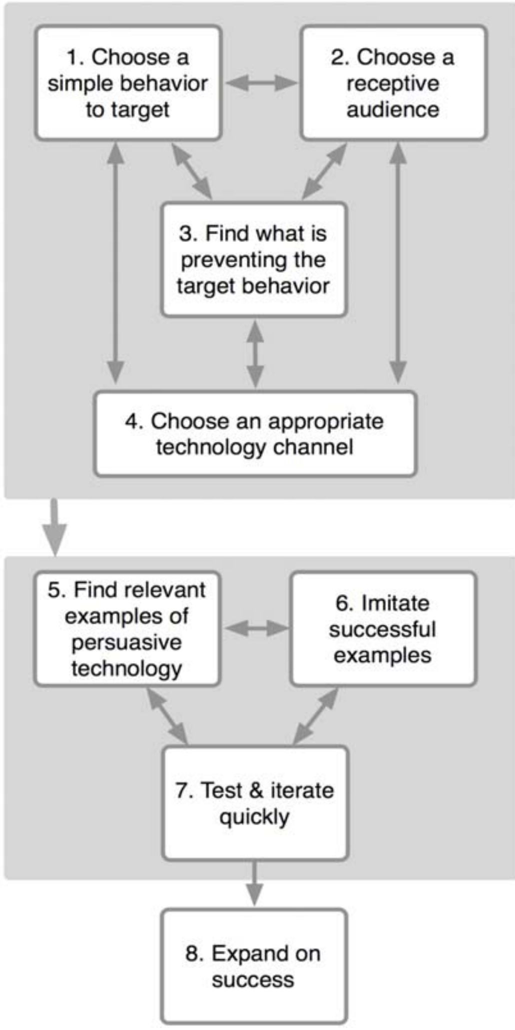


Figure 9 - Eight steps in early-stage persuasive design [Fogg 2009b]

Step 2 - Choose a receptive audience

Design teams often have so many things to worry about that, when creating a new persuasive technology, a resistant audience is simply not helpful. Step 2 therefore involves choosing the right audience for your intervention, ideally testing the technology on a receptive audience. Sometimes the audience will determine the target behaviour and vice versa, so the first two steps can be completed in any order.

Step 3 - Find out what is preventing the target behaviour

The next step is to determine what is preventing the audience from performing the target behaviour. Fogg lists three factors that prevent behaviour change, which mirror the previously described factors of attitude, knowledge or understanding and technology as described in section 2.1:

- Lack of motivation (Attitude)
- Lack of ability (Knowledge)
- Lack of a well-timed trigger to perform the behaviour (Technology)

Persuasive technology often requires more than simply the triggering of a desired behaviour. The solution must also boost the user's motivation or facilitate the behaviour, or both. Determining which is lacking allows the design team to focus their efforts.

Step 4 - Choose an appropriate technology channel

Deciding which channel is most suitable usually depends on three previous steps: the target behaviour, the audience and what is preventing the audience from adopting the behaviour. In the context of Fogg's persuasive technology and captology, this will be an electronics-based technology channel such as the internet, computer software, mobile phone applications and text messaging to name a few.

For example, consider a user that is not behaving in an energy-efficient way. If the user is lacking motivation, the design team should consider channels that leverage motivation, such as social networks. If however the user's ability is lacking, then an online instructional service that makes the behaviour easier, should be used, such as a guide showing where to buy low energy light bulbs, how to replace them etc.... If the family is lacking only a trigger to change their light bulbs to more eco-friendly versions, then email or text messages prompts and reminders might be suitable.

Step 5 - Find relevant examples of persuasive technology

Very simply, the team should search for examples of successful persuasive technologies that are relevant to their intervention, as defined in the previous steps. As an example, text message purchase reminders have been found to be an effective persuasive technology for advertising companies and products. Could these be trialled to remind people to buy energy efficient light bulbs the next time they are shopping?

Step 6 - Imitate successful examples

Instead of starting from nothing, a more effective method is to imitate what is already working and adapt the successful approaches from step 5 to the target behaviour and audience. Identifying and adapting successful technology examples to the design project at hand is the best possible way to create effective persuasive technologies.

Step 7 - Quick trials and iterations

Once a successful example of persuasive technology has been imitated, the next step is to test various persuasive experiences quickly and repeatedly. A series of small, rapid trials, lasting no more than a couple of hours each, will achieve a faster learning curve than one big study. These allow the design team to prototype the experience and see the reactions.

Step 8 - Expand on success

At this point emphasis should shift to expanding upon the success of the trials. The decision of how to expand depends on the team's goals or agenda. An argument could be made to promote a longer or more intensive response, or even a slightly different behaviour, building off the success of the first. By expanding the behaviour, other parts of the program are kept the same, including a similar audience, the same technology channel, the same underlying psychology and the same types of metrics. If the expansion works at least as well as the original then another expansion is in order. To continue the example, the text message reminders for light bulbs could be expanded for other products if found to be successful.

In addition to this eight-step process of best practice for designing persuasive technologies, Fogg [2003] developed a set of seven persuasive tools that can be employed in conjunction with one another:

- **Reduction,** the simplification of a procedure
- **Tunnelling,** guiding the user through a procedure, such as a software wizard
- **Tailoring,** individual customisation to the user's needs
- **Suggestion,** intervention at the most opportune moment
- **Self-monitoring,** allows users to track their own behaviour and receive feedback
- **Surveillance,** allows others to track the behaviour of users
- **Conditioning,** repetitive reinforcement

These tools are generalised persuasion techniques that have been distilled from good examples, proven to be successful and can act as prompts or relevant examples, for step

5, when developing new interventions. The strategy of surveillance can be a highly effective form of peer pressure but can give rise to a new form of rebound effect called the boomerang effect, where users question and reject advice and do the opposite of the intended persuasion [Petty et al. 1981]. This effect can cause below average users to increase their resource or energy use to match what they perceive others to be doing [Lockton 2008].

Although persuasive technology is based heavily on the field of computer interaction and interface design, there is obvious cross-over with Eco-Design and Sustainable Design approaches. The following section explores the work of Dan Lockton, who has formed an extensive collection of behaviour changing design examples and assembled them into a "Design with Intent" toolkit, much in the same way as Fogg's seven tools and use of successful persuasive examples.

2.3.4 Design with Intent

In 2007 Dan Lockton began collecting examples of how the design of products and the built environment influences people's behaviours, both intentionally and unintentionally. In the years since, he has collected hundreds of examples and began forming a design toolkit which used this database to guide designers in their efforts to influence behaviour [Lockton 2009] in much the same way that the TRIZ Contradiction Matrix [Altshuller 1996] does for physical design problems. Lockton organised his collection into eight different themes or "lenses" and associated prompts or "patterns", all of which are summarised here, taken from Lockton's 2010 paper entitled "101 Patterns for Influencing Behaviour Through Design":

1. **Architectural Lens** — *Angles, Converging and Diverging, Conveyor Belts, Feature Deletion, Hiding things, Material Properties, Mazes, Pave the Cow Paths, Positioning, Road Block, Segmentation and Spacing, Simplicity*

   The Architectural Lens draws on techniques used to influence user behaviour in architecture, urban planning and other related disciplines such as traffic management.

2. **Error Proofing Lens** *Are you sure? Choice Editing, Conditional Warnings, Defaults, Did you mean? Interlocks, Matched Affordances, Opt-outs, Portions, Task Lock in / out*

The Error Proofing Lens presents the target behaviour as an error which can be designed out of the system, either by making it easier for users to work without making the error, or by making errors impossible in the first place. It is often found in ergonomics, health & safety-related design, medical device design and manufacturing. A benefit for error proofing, in terms of sustainable design, is that it does not matter whether or not the user's attitude changes, as long as the target behaviour is met.

3. **Interaction Lens** *Feedback Through Form, Partial Completion, Peer Feedback, Progress Bar, Real Time Feedback, Simulation and Feedforward, Summary Feedback, Tailoring, Tunnelling and Wizards*

The Interaction Lens brings together some of the most common design elements of computer system interfaces. This lens also includes some patterns from Persuasive Technology, such as Fogg's tailoring and tunnelling [Fogg 2003].

4. **Ludic Lens** *Challenges and Targets, Collections, Leave Gaps to Fill, Levels, Playfulness, Rewards, Role-Playing, Scores, Storytelling, Unpredictable Reinforcement*

The Ludic Lens includes a number of techniques for influencing user behaviour that can be derived from games and other recreational interactions. Games are a highly effective way of engaging people for long periods of time, getting them involved and influencing people's behaviour through their very design. Yet this potential has been underexplored in application to other kinds of situations outside recreation.

5. **Perceptual Lens** *(A) Symmetry, Colour Associations, Contrast, Fake Affordances, Implied Sequences, Metaphors, Mimicry*

and Mirroring, Mood, Nakedness, Perceived Affordances, Possibility Trees, Prominence, Proximity and Grouping, Seductive Atmospherics, Similarity, Transparency, Watermarking

The Perceptual Lens combines ideas from product semantics, semiotics and ecological psychology about how users perceive patterns and meanings as they interact with the systems around them. Most are predominantly visual but they need not be: sounds, smells, textures and so on can all be used, individually or in combination. These techniques are often applied by interaction designers in the course of doing a job with or without necessarily considering how they can influence user behaviour.

6.	**Cognitive Lens**	*Assuaging Guilt, Commitment and Consistency, Decoys, Desire for Order, Do as You're Told, Emotional Engagement, Expert Choice, Framing, Habits, Personality, Provoke Empathy, Reciprocation, Rephrasing and Renaming, Scarcity, Social Proof*

The Cognitive Lens draws on research in behavioural economics and cognitive psychology. It looks at how people make decisions and how this is affected by 'heuristics' and 'biases'. If designers understand how users make interaction decisions, that knowledge can be used to influence interaction behaviour. Equally, where users often make poor decisions, design can help counter this.

7.	**Machiavellian Lens**	*Anchoring, Antifeatures and Crippleware, Bundling, Degrading Performance, First One Free, Forced Dichotomy, Format Lock In / Out, Functional Obsolescence, I Cut, You Choose, Poison Pill, Serving Suggestion, Slow / No Response, Style Obsolescence, Worry Resolution*

The Machiavellian Lens comprises design patterns which, while diverse, all embody an 'end justifies the means' approach that may often be considered unethical, but nevertheless are commonly used to control and influence consumers through pricing structures, planned obsolescence, lock ins and so on.

8. **Security Lens** *Coercive Atmospherics, Peerveillance, Surveillance, Threat of Injury, Threat to Property, What You Can Do, What You Have, What You Know, What You've Done, Where You Are, Who or What You Are*

The Security Lens represents the undesired user behaviour as something to deter and or prevent though 'countermeasures' designed into products, systems and environments, both physically and in computer systems

This extensive collection of behaviour-changing design features and techniques has been extracted from many different subject areas, from manufacturing product assembly to the built environment and human computer interactions, but it may also be used for the design of sustainable behaviour. Although the name "Design with Intent" has a certain level of ambiguity to it and gives no indication, on the face of it, that this may be a design for a behaviour-change tool, the benefit of this collection as a source of stimulus for designers is unquestionable.

In 2009, Lockton went to some length to describe how some of these "patterns" could be used for designing sustainable behaviour [Lockton 2009]. One such example is that of a closed-loop feedback system from the Error Proofing lens, where energy-inefficient behaviour is classed as an error and the product continuously monitors itself to avoid these errors, equivalent to electronic traction or stability control for cars.

The logical conclusion is that if the error correction was sufficiently reliable, users would no longer need to perform certain conscious energy-efficient behaviours at all. For example, consider a washing machine that could automatically switch to a half-load setting by weighing the load or even adjust washing cycles and detergent quantity by detecting the amount of soiling. All the settings could be processed automatically, maintaining the highest energy standards but no lack of convenience or function to the user.

Lockton [2008a] goes on to extrapolate this technology route to incorporate the Product Lifetime Optimisation Strategy of Chalkley et al. [2001] which says that if products were able to keep records of how they were used they could automatically disable themselves after a certain level of use. This would protect the product from overuse and potential damage, allowing manufacturers to retrieve their products in a predictable condition with a full use history and allow products to be replaced at an optimum point in their life cycle. This idea of error correction is developed further in the following section as a concept the author has called "Designing for Product Behaviour". The difference to much of the user-centred eco-design work described previously is that, in this case, the user behaviour remains unchanged and the responsibility lies with the product to act in an energy-efficient manner.

2.3.5 Designing for Product Behaviour

The idea of product behaviour is to use the design and features of the products to counter inefficient use by its operator so that, despite poor use, an optimal environmental result is always achieved. There is currently very little work on this subject, although it is touched on in Lilley's [2005] "Intelligent Products and Systems" (section 2.3.2) and Lockton's Design with Intent "Error Correction" (section 2.3.4). It is however used in the field of medical engineering from the point of view of safety, security and comfortable living for patients needing home care, rather than for energy efficiency [Dewsbury et al. 2001, Orpwood et al. 2005, Stefanov et al. 2004]. These medical papers look at the use of automated and assistive technology for the caring of patients at home. The work of Dewsbury et al. [2001] and Stefanov et al. [2004] look at the idea of a smart home for people with physical disabilities giving a good overview of how such a system could be implemented and constructed. However it is the design work of Orpwood et al. which shares a common concept with that of the author of this report and as such is of great interest here.

Orpwood et al. describe the ongoing work of the Bath Institute of Medical Engineering into studying the use of technology in a "smart home" to assist with home caring of people with dementia. People suffering from dementia suffer severe memory loss and have the inability to learn new tasks. Therefore it is very difficult, if not impossible, for them to change their behaviour. Their work uses prompts and reminders to the occupants or simply switches devices on or off automatically depending on the circumstances. The idea of a smart house is to use sensors to monitor the occupants' behaviour and respond to this information in an autonomous and appropriate fashion, in much the same way as a carer would, but operating 24 hours a day.

It was found to be most beneficial if the technology remained hidden and reacted in a similar way to having a carer in-house. One example provided is that of a new tap and monitoring system for the kitchen or bathroom, as people with dementia often forget to turn the water off. A conventional solution of using an automatic turn off, once the water had reached a set level, would remove all control from the patient and does not give the person a chance to resolve the issue themselves causing many patients to become confused and frustrated. It was found that in many similar situations, carers tend to employ a three-stage response.

1. They provide a reminder, for example ''don't forget you've left the bath running'';
2. If the user does not respond to the reminder, they intervene to turn off the tap;
3. They let them know what they have done, for example ''your bath is ready, I've turned the water off''.

Orpwood et al. have tried to emulate this three-stage response in a tap design product which can automatically turn off if the water gets too high, but does not lock the system, allowing the user to add a little bit more if they wish. This emulates the situation of the user having turned it off themselves, keeping the patient in control. This has proved successful as it operates in the way taps always have done, but with the security of not endangering the patient.

> *"The main conclusion from the research work on monitoring is that any monitoring of human behaviour in order to make judgements is not going to be straightforward. The judgements made are always going to be probabilistic, and the designer has to incorporate means of dealing with errors, particularly in safety critical situations such as cooker usage."*

Although the design for product behaviour work incorporated into the smart homes of Orpwood et al, Dewsbury et al. and Stefanov et al. have the safety of the occupant as the paramount consideration, there are many ethical questions surrounding this topic of product behaviour and the wider context of designing for behaviour change. The following section is based heavily on the work of assistant professor of the philosophy of technology, Peter-Paul Verbeek [2006] at the University of Twente in the Netherlands. His research into the morality of technological artefacts and its implications for ethical theory and design practices is unquestionably relevant to this subject and should be explored in greater detail.

2.3.6 Ethics of Design

Products and technologies have been shown to profoundly influence the perceptions, behaviours and experiences of users. Hence, the ethics of engineering design must be tasked with conceptualising this influence and anticipate it in the design. The basic premise of products is that they are designed to deliver a particular function or need, so satisfying some desire of the user. As a consequence the ethics of such engineering are concerned only with the quality in which the product delivers this goal. A low standard of product may cause injuries or deaths when used, or the way in which it functions may negatively affect the environment in which it operates.

The idea that a product can have a 'script', as first developed by Akrich and Latour in 1992 and introduced in section 2.3.2, brings this purely functional vision of technology into question. The scripts give products additional functionality which may act subconsciously on the user, such as the classic example of a plastic cup versus a porcelain cup described earlier. These hidden scripts can and often are designed into products but are also largely dependent on cultural backgrounds, the attitudes and beliefs of the user.

Latour stated that designers anticipate how users will interact with their product and, implicitly or explicitly, build the scripts for use into it. The designers are delegating specific responsibilities to the artefacts, such as the responsibility to make sure nobody drives too fast being delegated to a speed bump. Verbeek argues that conceptualizing artefacts in terms of scripts shows that functionality is too limited a concept for engineering ethics. Scripts transcend functionality and occur once the technology is functioning. When technologies fulfil their functions, they also help to shape the actions of their users. The script approach opens up a new way to morally assess technologies with respect to the role they play in their use contexts. In doing so, it also reveals a specific responsibility of the designer, who can be seen as the inscriber of scripts.

Technology and the way it interacts with the user can have profound effects. The ethical standpoint of this is often overlooked if the scripts are not considered in the design of the product, but ethics must be considered when the intentional aim of the design is to change or limit behaviour.

Verbeek suggests that designers should try to establish a connection between the context of design and the context of use. Thus formulating product specifications based not only on the desired functionality but also on a prediction of its future role and any scripts that maybe associated with it. It is on this prediction that a moral assessment should be made. His research suggests that there are two ways this prediction can be made. The first is quite simply for the designers to imagine the product in use considering how it could be used or misused and how this might affect the user and incorporating these insights back into the design process. The second approach is for designers to involve all relevant stakeholders in the design stages of the product. This might involve meeting users, relevant pressure groups and companies and trying to reach a consensus decision.

This draws many parallels with User-Centred Design where the aim is to understand the context of how a product is used so as to better improve its usability [Norman et al. 1986] and Gould's design work stressing the importance of an early and continuous focus on users [Gould et al. 1985]. The fact that products and technologies will always affect human actions charges designers with the responsibility to anticipate these roles from an ethical standpoint. This anticipation is a complex task as the effect is not entirely predictable, but lessons learnt from User-Centred Design and user involvement in the design process will help.

For the User-Centred Eco-Design approach developed in this thesis, the question of ethics is coupled with the question of commercial acceptance. The redesign of consumer products is inextricably linked to commercial success and product sales. In this regard the ethical responsibility of the designer can be partially alleviated by the knowledge that a successful product, in the long-term, will, by definition, not subject the user to a situation or function that they were not happy with. Thus the designer should ensure that any environmental design interventions continue to support the needs of the user and add to the desirability of the product.

2.4 Research Direction

In summary, section 2.3 (Designing for Behaviour Change) has presented the context for the author's research, presenting more detail on the gaps in the knowledge, with the previous two sections: Understanding Energy Using Behaviour (2.1) and Changing Energy-Using Behaviour (2.2) as justification for the research focus. Under whatever name it takes, a strategy that uses the design of the product to change energy inefficient behaviour has considerable merit and advantages over policies that purely ask or attempt to persuade users to be more energy efficient. As part of this researcher's review of the design strategies and research discussed in the previous sections, four key design principles have been created to encompass all the different approaches: influence, prohibit, counter and adapt.

Influence Based on the idea of scripts, persuasive technology and the default bias [Lucia 2007]. This approach uses technology to prompt or encourage a particular behaviour, pull handles on a door, speed bumps, etc. However relies partially on the intended user sharing the same contextual understanding of the script as the designer.

Prohibit Utilises the design of a product to prevent an undesired behaviour from happening in the first place, for example interlocks and error proofing.

Counter A product-behaviour approach that works with the existing undesired behaviour, keeping the behaviour unchanged but now with a reduced energy impact. An example would be the automatic engine switch-off that now features on many cars. The driver's behaviour of idling for long periods at traffic lights is not changed but the car is now more fuel-efficient.

Adapt A second product-behaviour approach, more heavily focused on an intelligent product design, where the product monitors its use and adjusts itself to suit how it is being used. Consider a washing machine automatically choosing its own settings, or a television screen where the picture is turned off if it detects no one is looking at it.

With these four design principles it is possible to create a User Behaviour / Product relationship matrix, figure 10, showing the available strategies for promoting sustainable product use and drawing clear parallels with Igor Ansoff's 1965 corporate strategy matrix [Lowy et al. 2004], described in greater detail later in this section and shown in figure 12.

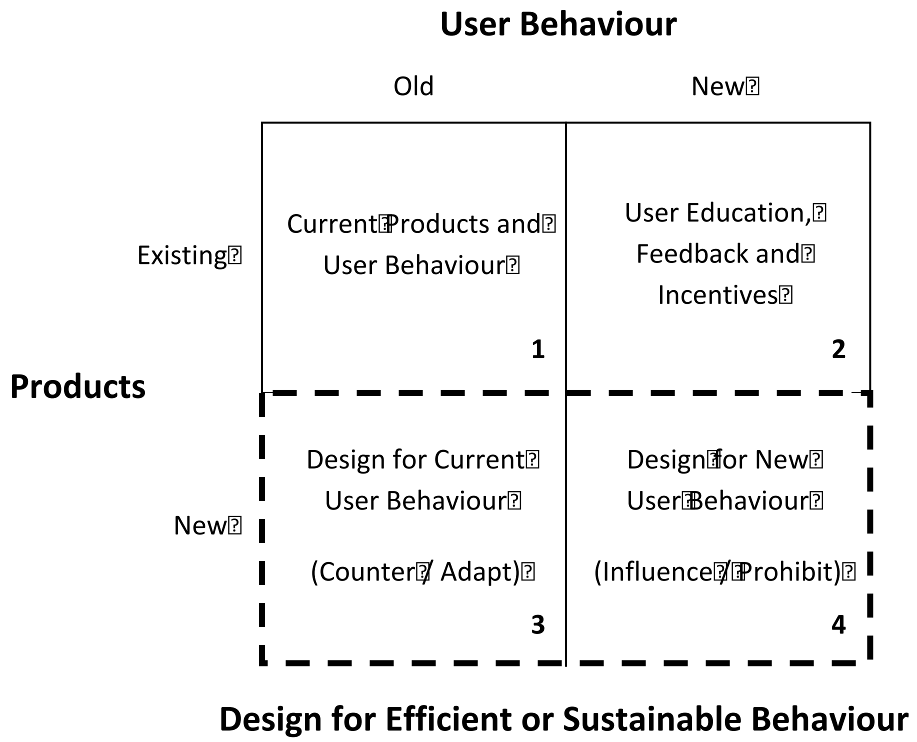


Figure 10 Behaviour / Product Relationship Matrix for deciding the most appropriate strategy for improving energy efficiency [adapted from Elias et al. 2007]

Square One This square represents the current situation, current products and behaviour. The aim is to improve energy efficiency by moving from this square to any of the other three.

Square Two The aim of this square is to change the behaviour of users but keep the existing product function unchanged. It is the strategy of improving the user without changing the product. Thus it is reliant on education, providing information, feedback and financial incentives so that the user may be influenced for the better. This is the traditional method of curbing inefficient product use and has been discussed thoroughly in section 2.2.

Square Three This square moves the designer into a field of designing new products, where the design of the product has been changed but the user's behaviour has not. This box presents a strategy which may focus more on the traditional engineering and material efficiency of products, working within the existing boundaries of the current behaviour but also gives the potential for the development of products which can counter or adapt to current behaviour. Designing for improved product behaviour produces products that can correct inefficient use without the user being aware of any change. It is important to note that these designs must not prevent a user from being energy-efficient on their own, as efficient users may become lazy, relying on the product to do things for them and lowering their efficiency to a base level set by the product.

Square Four The final square requires new products to be designed which force a new behaviour, designing new products and new good behaviour. Since a new behaviour is intended, this may present the designers with additional problems such as the ethics of their design and unexpected rebound effects. Conversely, this might not be such an issue for the products in square three since the behaviour is already known.

In order to move from square one (the current situation), by utilising an environmentally beneficial product-use strategy, the user will be subject to at least one of the other three squares available. For this movement to be successful and a sustainable change made, the designers must look at the user's latent needs, their inefficient behaviour and the available or developable technology.

Figure 11 gives some product examples of each of the four squares from figure 10. Square three, new product but old behaviour, will in some cases be more acceptable to users, an easy incremental improvement avoiding many complicated ethical issues and as a result might be more commercially viable for many physical products. For virtual products such as computer software, for which Fogg focuses much of his work, a jump to the 'new - new' user behaviour focus, shown in square four, may be more effective and easily facilitated.

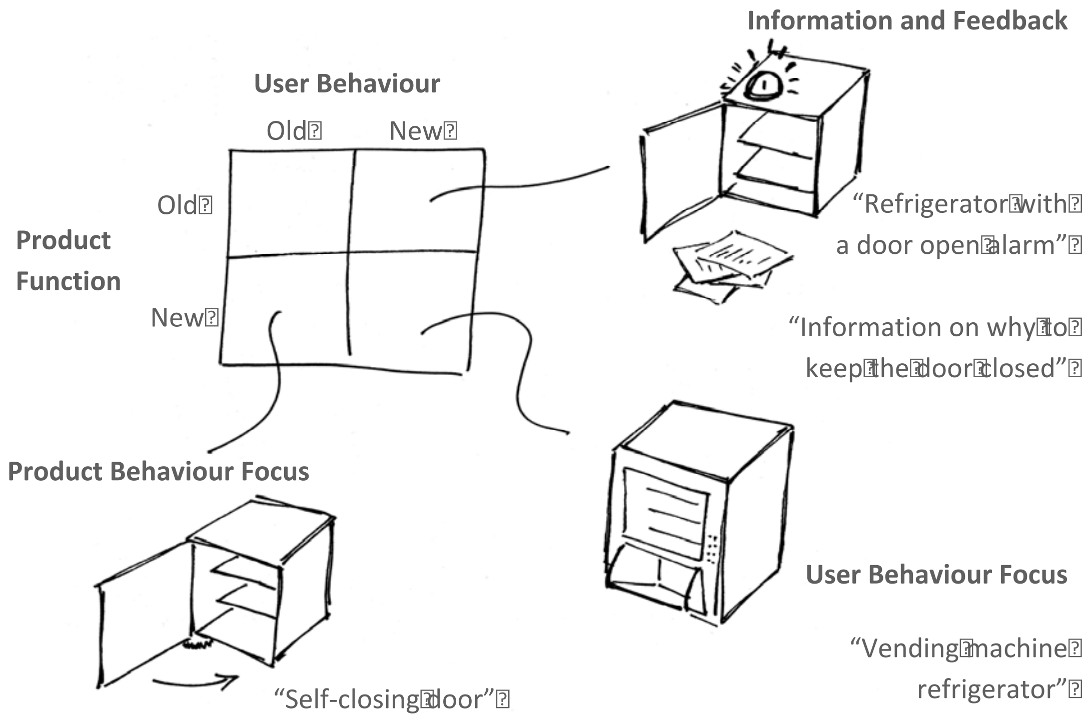


Figure 11 The Behaviour / Product Relationship Matrix with design focus and example solutions for a domestic refrigerator

Ansoff's corporate strategy matrix showed the available choices between developing new products or new markets when increasing corporate growth (figure 12). By comparing it to the new Behaviour / Product Relationship Matrix from figure 10, it is also possible to estimate a level of risk associated with each sustainable use strategy.

		Market: Old	Market: New
Products	Existing	Market Penetration **Low Risk**	Market Development **Medium Risk**
	New	Product Development **Medium Risk**	Diversification **High Risk**

Figure 12 Igor Ansoff's 1965 corporate strategy matrix

A product behaviour-focused option, as shown in square three, is perhaps for some products, such as domestic appliances, a more obvious, incremental design process. Thus improving the technology efficiencies and product behaviour so as to adapt to and counter inefficient behaviour. For products such as these the user behaviour-focused solutions would be higher risk, innovative projects with perhaps no previous product basis or behaviour experiences for improvement to be based on.

Whichever approach is adopted by the designers, it is crucial to provide them with as much information and data as possible on the user, the undesired behaviours and the energy impact of their actions. Without an established metric and measurements for the impact of the relevant behaviours it is impossible to know whether the new design is an improvement over the old. Up until this point, much product redesign work in this field of sustainable behaviour has been conducted solely on qualitative information.

This research aims to rectify this and provide:

- A technical framework for measuring and analysing the energy losses of products;
- A user-centred method of investigating and recording the behaviours in question;
- A way of presenting this information to a design team and its effective utilisation.

Having answered research objective one (What are the existing approaches to reducing inefficient energy-using behaviour?) and its three questions. These three research aims seek to address research objectives two (How can the energy impact of user's behaviour be measured?) and three (How should designers use information on behaviour to design products?). But in order to proceed with this research and empirical studies, a detailed look at the research activities to be undertaken must be made. Passing a critical eye over the research methods proposed, the next chapter describes the methods used and explores some of the issues of reliability and validity associated with them.

Research Questions (RQ)		Research Activity	Chapter

Objective 1: To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour

RQ 1.1	What is poor energy-using behaviour?	Literature Review	2.0
RQ 1.2	How can it be changed?		
RQ 1.3	Can behaviour change be designed?		

Answered

Objective 2: To create a way of measuring the energy impact of user's behaviour

RQ 2.1	What are suitable metrics?	Energy Modelling	4.0
RQ 2.2	How significant is poor energy-using behaviour?	Use Scenarios	
RQ 2.3	How can information on behaviour be collected and turned into useful data?	Observational Studies	5.0

Objective 3: To explore how designers might use information on behaviour to design

RQ 3.1	How can this information be used to aid the design of products?	Literature Review	6.0
RQ 3.2	How do designers interact with this information?	Design Experiment	
RQ 3.3	How should this information be presented?		
RQ 3.4	What impact will it have on the design output?		

Objective 4: To investigate if it is possible to design products so that they can only be used in an energy-efficient manner

RQ 4.1	What would such a design process look like?	Participatory Research Design Process Demonstrator Industrial Consultation	7.0
RQ 4.2	Can a product improve the impact of poor energy-using behaviour?	Product Demonstrator	

Research Progression and Chapter Outline

3.0 Research Methodology

The literature review investigated the reasoning why despite an improved education, better energy awareness and knowledge of the global importance of energy and climate change, pro-environmental behaviour has been difficult to encourage and has on the whole, failed to materialise in any substantial form. The resulting research direction is thus to champion a design-led approach to behaviour change. The very nature of this research, the study of human behaviour, the measurement of that behaviour and the study of designers using these measurements, places it in the field of empirical study and social science. Guidance must therefore be taken from this field when establishing what research methodologies are suitable and also on the reliability and validity of the research outputs [Bryman 2001]. The work also uses the emerging design research methodologies of Blessing and Chakrabarti [2009].

This chapter describes and outlines the main research activities undertaken in this thesis, detailing information on the methodologies used, the reasons behind their choice and any issues encountered. The large variety in the scope of the research objectives and the corresponding research questions, from section 1.3, leads to several methods being employed within this research.

3.1 Overview of Research Activities

The first research objective (To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour) has already been answered in chapter 2.0. Therefore the remaining three research objectives of this thesis required work that could be fulfilled by completing the five research activities of energy modelling, energy audits, user studies, a design experiment and the evolution of a new design process. This section provides a brief overview of: these research activities undertaken; the justification for their choice; how the study participants were selected and some of the issues or concerns that may have arisen from the choice of methods or their execution.

Figure 13 shows the sequence of these five research activities and the research method options for executing them. The methods chosen are highlighted in the diagram and the reasons for their choice are described in the relevant sections of the chapter. The first activity is a development of an energy modelling framework used to demonstrate the possible impacts of energy-inefficient behaviour. The activities then develop into practical fieldwork, user studies and design process creation and evolution. These activities and methods are summarised in the research methodology sections which follow, with further discussion and detail of each in the relevant thesis chapters along with the corresponding results.

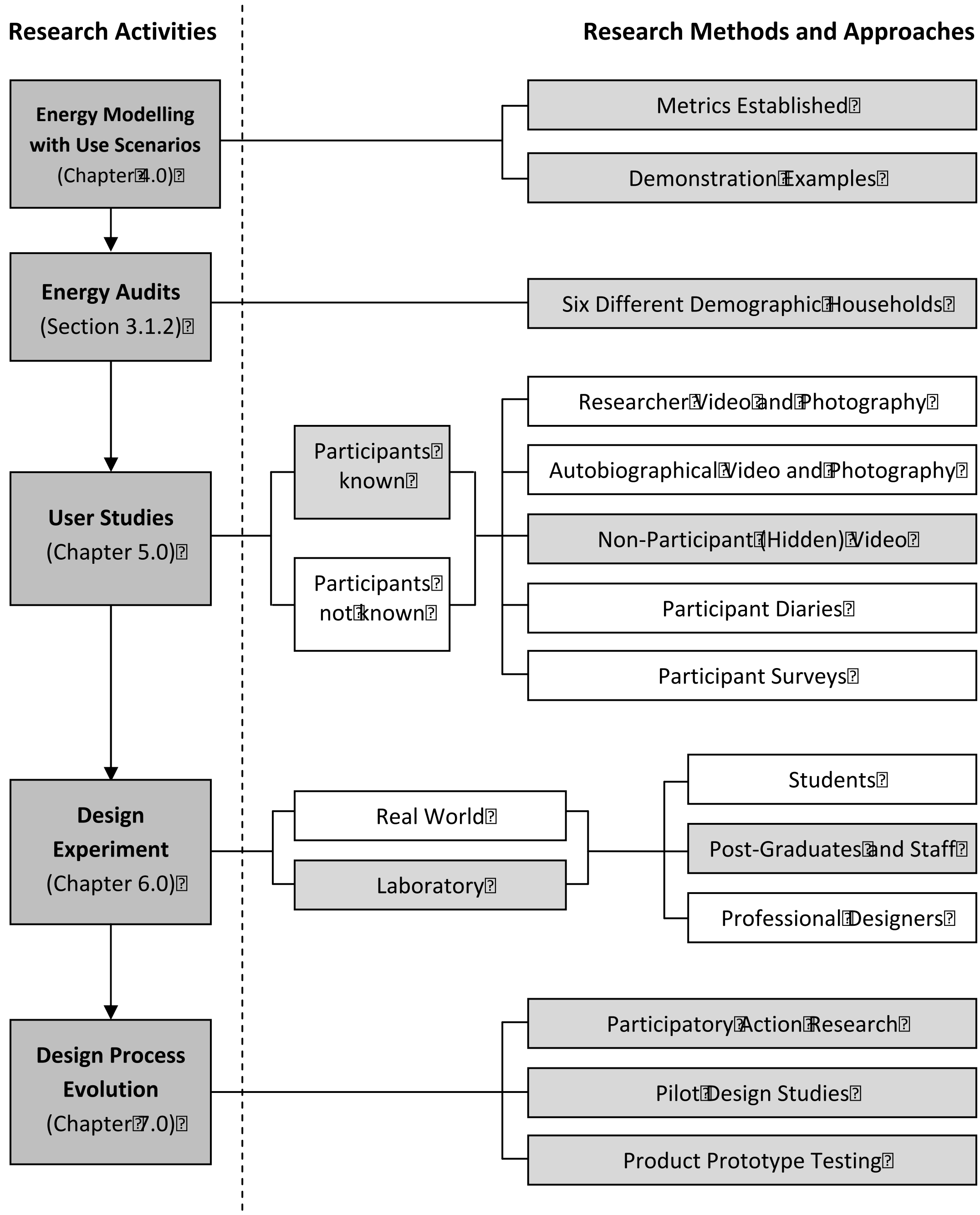


Figure 13 - Research Activities with the Approaches Followed Highlighted

3.2 Energy Modelling with Use Scenarios

The aim of this research is to reduce the environmental impact, in terms of energy use, of user behaviour through the design of products. The literature review explained why this is desirable (section 2.3) but there is a lack of quantitative research into the sizes of these impacts at the individual product level and the large variety of different behaviours that actually determine the size of the impact. Research from related fields of study suggests that the best way to do this is by modelling and simulating the impact with use scenarios [Moss et al. 2010].

Originally developed by the military in the 1960s, the use of models with scenarios are now commonplace in the field of climate change prediction and assessment. The goals of these are to better understand the uncertainties involved in a given situation in order to reach decisions that are robust under a wide range of possible futures [Moss et al. 2010].

This work is dealt with fully in chapter 4.0 where models based on use scenarios, called Product Energy Profiles (PEP), are developed to quantify in energy terms, how particular behaviours effect the energy use of a product. The aim of these PEPs are to give designers and engineers the evidence they need to make an informed judgement as to what should be the focus of their endeavours and draws many parallels with methods commonly found in Failure Mode Effects Analysis (FMEA) [Stamatis 2003]. For the introduction and explanation of these PEP models three products are chosen and two scenarios of product-use devised for each. These fictitious scenarios are meant to represent a situation in which the product *could* be used, for example the decision to watch television for 45 minutes, and are meant for demonstration purposes only, presenting both a small and large energy impact. They are meant to be easily understandable but not definitive. It is the work of the user studies in chapter 5.0 to provide rigorous data that could be used to form a set of scenarios that are representative of typical behaviours.

The use of fictitious scenarios has one large benefit to practitioners. Using only limited and easily obtained or estimated data, they can provide a simple theoretical simulation giving the rough proportion of energy used that is associated with user behaviour. The results of this are therefore essential to guide whether a time consuming detailed user study is required at all. It is an important first step in the assessment process and valuable to an industrial audience considering conducting user-related studies of their own.

3.3 Energy Audits

As an initial scoping study, the first user-related study undertaken was that of a simple domestic energy audit [Bartiaux et al. 2006]. It was designed as a simple check of the literature on the energy values of common domestic products [Mansouri et al. 1996] and as a precursor to the more detailed user studies of chapter 5.0. The research was to focus on the energy impact of domestic electrical goods, products and appliances, due to their abundance and ease of access, as well as their high energy use and global significance. This researcher approached six domestic residences, each representing a different social demographic and covering the widest possible variety of ages and family situations:

1. Single Professional
2. Professional Couple
3. Multiple Occupancy Student House
4. Family with Young Children
5. Family with Teenage Children
6. Retired Couple

A short interview and questionnaire was prepared for each house, listing 47 typical electrical goods, their measured electrical energy-use and the amount of time they would typically be used, with space to add additional items if required. The first half of the interview asked about the type of house, how many people lived there and a description of the resident's typical day and work patterns. The second half involved being led around the house taking descriptions of electrical items and then monitoring and recording the electrical energy-use in both the 'standby' and 'on' modes of each item. The households were asked to say how often each item was used per day, per week or per month. From this data a total energy figure could be estimated for every item per day. The consumption of gas powered devices, such as water heaters for showers or gas cookers was converted to the base unit of kWh for the purposes of comparison. This was not thought to have affected the results either way since electrically powered equivalents are in common use in the UK and the user behaviour associated with one device is not thought to change sufficiently if they had the other instead.

This study is reported in full in Elias et al. [2007] with the relevant details and results included in Research Appendix 9.1. The results of this simple audit showed that five of the top ten energy-using products for all the households could be found in the kitchen (Research Appendix 9.1, table 25). When the energy-use values for the top 20 products and all six households were combined, the kitchen, in this study, was shown to be the highest energy-using room in the house, three times that of the living room [Elias et al. 2007]. It was therefore decided that a more detailed user study would be undertaken on the kitchen and specifically on just the behaviours relating to the refrigerator, as the single largest energy-using product. It is the methodology behind these detailed user studies that will now be described in the following section.

3.4 User Studies

Learning how a user interacts with and uses a product provides valuable insights for new product development. Traditionally, designers would try and obtain this information by conducting customer surveys, operability assessments, focus groups and field trips [Blomberg et al. 1993, Maguire 2001]. Each of these approaches have strengths and weaknesses but are often carried out in the later stages of a product's development. This means that designers could do little more than verify that a design is acceptable [Blomberg et al. 1993]. The field of User-Centred Design (UCD), introduced in the literature review, emerged in response to address this problem.

UCD uses numerous techniques and methods for understanding users [Vredenburg et al. 2001, Maguire 2001], such as: Context-of-Use Analysis; Focus-Groups; Use Scenarios; User Personas; Field Studies and User Observations; Diary Keeping and Post-Experience Interviews, to name a few. The use of these methods early in the design process can provide valuable insights into the complex relationships between people, products and their environment and reducing the potential for poorly designed products [Lofthouse et al. 2006]. One method that has proliferated in recent years is that of field studies and user observation, also known as ethnography [Anderson 1994, Forsythe 1995, Dourish 2006, Buur et al. 2007, Segelström et al. 2009].

Ethnography originated from traditional anthropological and sociological research and is fundamentally based on observational studies of people [Simonsen et al. 2000]. However it seems to have lost much of its rigour and purity when taken up by designers, as the goals of design research tend to be more applied in nature [Ball et al. 2000, Simonsen et al. 1998]. Design researchers use ethnography with the principal motivation being the axiom that 'what people say and what they do are not the same'. There are many ways to conduct these observational studies, from hidden video studies in which the observer is as unobtrusive as possible, to the other extreme of a participant observer. In participant observation the researcher becomes a full participant in the activities studied, gaining first-hand experience of the events or people being studied [Blomberg et al. 1993]. It is this ability of ethnography to describe social settings as it is perceived by those involved that underpins its appeal to designers [Hughes et al. 1997]. Although much has been written about ethnography and ethnographic field methods, there is no agreed method to guide field work and so Blomberg et al. [1993] usefully set out a few guiding principles:

Preserve Natural Settings	Conduct the field work in the everyday settings in which the product would be used, as particular behaviours will only be understood in the everyday context in which they occur.
Be Descriptive	Describe how people actually behave and avoid being judgemental.
User's Point of View	Research methods should be aimed at getting as close to an insider's view of the situation as possible. Try to understand the world from the point of view of those being studied.

Increasingly video cameras play an important role in ethnographic studies and are uniquely suited to support a user-centred design methodology [Brun-Cotton et al. 1995]. They allow recordings to be reviewed at a later date or by different people and have become an accepted industry standard for user observation and data collection [Dourish 2006, Buur et al. 2007, Segelström et al. 2009]. In practice, video recordings are commonly collected as part of a pseudo-ethnographic 'quick and dirty' study [Hughes et al. 1994], where a researcher videos and records the actions of users in different situations, perhaps asking them to describe their experiences as they use a particular product or service. For the context of this research the term ethnography refers to the meaning designers have placed on it, that of a data-collection approach [Buur et al. 2007].

3.4.1 Review of Key Techniques

The energy audits described in the previous section reveal that the kitchen is an ideal setting for a user study since there is a good concentration of high energy-using products located there, with the refrigerator being the largest one. Bearing in mind the comments above what was required was a method for obtaining quantifiable data as to which products were being used, for how long and why? There are currently a number of suitable research methods that have been used in the past for similar objectives and these will be reviewed as to their suitability for this research. The ones chosen are:

- Researcher Video and Photography
- Autobiographical Video and Photography
- Non-Participant (Hidden) Video
- Participant Diaries
- Participant Surveys

This section will go into detail describing each of these in turn, highlighting advantages and drawbacks of each. It concludes with an assessment of the challenges facing any user study and the reasons behind the chosen method of Non-Participant or hidden video recordings:

- **Researcher Video and Photography**

  This method of the researcher holding the camera and following a participant, with or without a commentary description, undertaking the studied activity is commonly used in the design industry [Anderson 1994, Blomberg et al. 1993, Forsythe 1995, Hughes et al. 1994, Dourish 2006, Buur et al. 2007, Segelström et al. 2009]. This can then be followed by a confirmation survey and key informant interview for an additional level of validation [LeCompte et al. 1982a]. In this context an experienced researcher will follow the actions of the subject, aware of the fact that the camera can often prove an unwelcome hindrance to the rapport between the two. The presence of a camera is a constant reminder that the subject is being interviewed [Belk et al. 2005].

- **Autobiographical Video and Photography**

  This differs from the research video in one critical aspect: the participant is in charge of the camera, with no researcher present during filming and is referred to as being an "autobiographical" or "autovideographical" technique. Without the presence of a researcher, the participants are often more spontaneous and self-directive in their behaviours, recording the things that are important to them rather than those of the researchers [Belk et al. 2005]. Coupled with interviews after the images have been reviewed and participant diaries of the studied period, Rodriguez et al. [2005] found this to give a useful account of the thinking and reasoning behind the participant's behaviour when using domestic goods and appliances.

- **Non-Participant (Hidden) Video**

  Hidden cameras and other "fly-on-the-wall" video methods are forms of non-interactive ethnography and are also known as Non-Participant Observation as no participant researcher is present [Bowman 1994, Elliot et al. 2003]. It can be undertaken in three different forms [LeCompte et al. 1982a]:

  1. Stream-of-Behaviour Chronicles - Recording and analysing the streams of participant behaviour in accurate, minute-by-minute accounts of their actions and speech;

  2. Proxemics and Kinesics - Concerned with the social use of space and body movements;

  3. Interaction Analysis - Recording the ways in which participants interact with one another.

  These non-interactive forms of data collection have a number of advantages over video-based methods. First, they gather a large amount of raw data, without initial filtering by the researcher, which could be re-analysed at a later date to prove new hypotheses. Second, they do not require a skilled researcher, experienced in the recording of social situations and conditions. Lastly they can be replicated more easily as any variables relating to the researcher are controlled. This ability to replicate the study more easily increases the reliability of this hidden method [LeCompte et al. 1982b] and allows other researchers to replicate the approach themselves. It is also essential to note that when using video or photography methods that involve hidden cameras, it is of the utmost importance that good research ethics protocols are followed.

- **Participant Diaries**

  The use of participant diaries is an established method commonly used for research activities requiring a daily log or time budget, such as the recording of nutritional intake or television viewing hours [Dillman 2000]. When trying to understand user behaviour, diaries can encapsulate a lengthy, mostly non-observable process, going beyond the simple 'counting' and 'collecting' to 'describing' and 'reflecting' [Toms et al. 2002].

This method is again often used in conjunction with interviews before and after the data collection period. First establishing a rapport with the participant and collecting some baseline data and then after the diary is finished, meeting to validate and clarify the data. With this method it is possible to collect a large amount of detailed and in-depth data from a wide range of people, increasing the sample size cheaply and easily perhaps over a wider geographical area. The primary disadvantage however is the potential unwillingness of participants to comply with the requirements of the diary regime [Lewis et al. 2004].

- **Participant Surveys**

  In the context of energy use, researchers can often assume too much knowledge on the part of the participant to know, or to remember, the actions which they have taken, giving false images of the actions undertaken. There is also scope for a wide degree of error depending on the way the survey is written and presented. Participants have been shown to change their responses depending on how the 'answer space' is presented, as scales and 'tick box' options can suggest certain meanings and give impressions of normality or average [Bertrand et al. 2001]. However surveys have the ability to reach a large audience and thus address their weaknesses with the advantage of a large sample size.

3.4.2 Limitations and Challenges for User Studies

With all of these different research methods and approaches to choose from, some working in combination with others whilst others working alone, it is important to investigate the issues, limitations and challenges that face any user study:

- **Risk of the Hawthorne Effect**

  The people being studied can change their behaviour in order to gain favour with those studying them. If the participants are aware of being investigated or are knowledgeable of the objectives of the study their behaviour could change jeopardising the validity of the test [Blalock et al. 1982, Mansouri et al. 1996, Rodriguez et al. 2005];

- **What people say is often not what they do**

  A common problem experienced with surveys and interviews in the social sciences is that the stated attitudes of participants towards a given situation is simply not carried out when put to the test [McKenzie-Mohr et al. 1999]. Also, when asked a series of subjective questions, the responses are not consistent over time, suggesting that the attitude may not exist at all [Bertrand et al. 2001];

- **Difficulty in finding candidates**

  The longer, more intrusive and generally more revealing the research method, the harder it can be to find suitable candidates to take part. The methods required to uncover the truth behind a user's actions will likely involve a greater degree of invasion of that person's privacy and is thus likely to be resisted.

- **Time consuming**

  Video information, although invaluable in certain situations for capturing occurrences and moments, perhaps too quick or too subtle for a researcher to note at the first instance, has a drawback: the process of analysing the footage can be lengthy. One hour of video footage can take three hours to analyse [Bhamra et al. 2007].

3.4.3 Justification for the Chosen Method

With all these factors to consider, it was decided that the kitchen, highlighted in the energy audits of the previous section, would be the subject of a non-participant hidden camera observation study. This non-participant camera method was chosen because it would address as many of these factors as possible and in particular offered the following advantages over other methods:

- The aim of the study is to uncover quantifiable data on user behaviour; this requires a great deal of repetition of simple normal behaviours in order to establish the validity of the data. This method would allow for many days of footage to be recorded at all times of the day;
- The absence of a researcher would avoid any bias that may result and could prevent the capture of true behaviour;

- It would be more easily repeatable by other researchers.
- Since the specific subject of this first study, a particular product in the kitchen, was at the time unknown, collecting raw data of the whole kitchen was essential to avoid constant revisits and new studies being needed.

However, as noted previously, it was going to be hard to find willing participants and so for the first study, the researcher's own home was used. This multiple-occupancy residence, where four adults lived, had already been audited and presented a number of practical advantages. Firstly the video equipment could be tried and tested, using this study as a pilot for future studies. Secondly the time frame from the study was flexible and extendable: if the camera needed to be adjusted or additional data collected, it could be done so with the minimum of difficulty.

For the second kitchen study and to make the results more wide reaching, a second demographic was chosen, that of a family with young children. Again there were the limitations of needing participants to volunteer such an intrusion of their privacy. Thus the research supervisor kindly volunteered her house. The family consisted of her, her husband and three year old son.

The setup, data collection methods, coding and analysis are dealt with in detail in chapter 5.0. However, the results from the first study gave no indication that the participants' behaviour had changed during filming. As a result, this researcher was confident that despite the supervisor being aware of the research goals, the long length of the study would result in the presence of the camera being forgotten and normal life being recorded [Vinten 1994, Anderson 2004]. The footage from this second study also showed no indication of unusual behaviour and matched with the previously obtained descriptions the participants gave of their typical week during the energy audits.

3.5 Design Experiments

Design researchers have used experiments and observational studies extensively over the last forty years to explore the working practices and performance of designers or design teams [Cross 2007]. A significant amount of current research in engineering design is based on some sort of design experiment [O'Hare 2010]. A design experiment uses the principles of the 'Scientific Method' to apply rigour and structure to test situations and hypotheses that would be difficult to replicate outside of laboratory conditions.

This research method is best suited to the research questions to be dealt with in chapter 6.0 where the researcher aims to uncover insights into how a design team can best use information in the early stage design process. Although other methods could be used to uncover this information, such as the use of surveys and interviews to ask designers how they use information or researcher-participant witnesses in the design process, a design experiment was decided upon for the following reasons:

- To uncover this depth of information would have required a great deal of sensitive access to the workings of several professional companies and in many different settings;

- It relies strongly on suitable design work being performed at the current time;

- The study would have to be more specific, focusing on a research question and less exploratory;

- The variables relating to the designers themselves would not be controllable;

- The majority of the experimental variables could be controlled to give a repeatable process that other researchers could replicate.

For these reasons, the idea that this investigation could be conducted in a laboratory setting had too many practical advantages [Cash et al. 2009], although there has been a distinct lack of scientific rigour when using design experiments in the past [Blessing et al. 2009]. This was then compounded by a failure of many researchers to provide necessary details of their research, such as the methods for data collection and analysis [Bender et al. 2002]. In particular the issue of repeatability is crucial and it is argued that the way that the work was conducted was such that researchers from around the world could repeat the experiment should they wish (see Reporting of Methods, section 3.5.2).

As a result, great care has been taken to ensure that the reporting of the design experiment here is adequate to support any conclusions. Listed below are the main issues that appeared when planning and conducting this design experiment and also the principal mitigation techniques used. In this context mitigation means the steps that were taken to reduce the impact of a particular issue on the validity of the experimental results.

3.5.1 The experiment context

This includes both the context of the participants and the situation in which they find themselves. This also covers any pre and post-experiment conditions, the technology and methods used as well as the data handling procedures. The correct handling of this context is an essential element in qualifying the significance of the results as well as allowing an informed judgment to be made about the real world value, validity and applicability of the study.

Participant context was recorded through a description of the participants' educational and social background, this researcher's personal knowledge of their backgrounds, working partnerships and friendship circles, as well as the use of the Belbin tests to aid in the balancing of the teams.

It is also worth noting here that the effect of variances in the abilities of individual participants presents an additional problem in small scale studies such as this. As a result the use of balanced teams (rather than individuals) and qualitative analysis was used to support any quantitative assessment.

Situational context of the participants was maintained and developed through a strict non-disclosure of experimental goals, methods or team membership to any participants before the experiment as well as non-disclosure of the participants' role in this design objective.

3.5.2 Reporting of methods

Bender et al. [2002] stated that there is a frequent failure of many researchers to provide necessary details of their research, essential, in the scientific sense, for this experiment to be repeatable by other researchers and thus for its results to be verified and confirmed. To that end care was taken to thoroughly define context, terms and techniques throughout the study. The use of standard, easily available and understandable procedures can be found in extensive detail in Cash et al. [2011a].

In addition to this the provision of written methods and supporting material such as the instructions to the participants has been made available on a freely accessible website: www.designresearchmethods.com. It is hoped that by doing this, the study may be repeated by other researchers and its context within the larger body of design research work can be defined.

3.5.3 Control techniques used

The primary control technique introduced into this experiment was the involvement of a placebo control group, an underused control technique in design research [Cash et al. 2011a], in addition to the normal no-treatment control group. This had several advantages over the standard no-treatment control group being used alone. First, the results of the placebo group allow for the normalisation of the experiment and removal of experimental effects other than those directly under study. Lastly, the use of the two control groups, in conjunction, allows the experimental hypothesis to be isolated effectively from other experimental factors. A secondary control technique was the use of triangulation whereby qualitative and quantitative analysis methods were used to explore the significance of any findings. This allowed differences between measures to be identified and discussed, helping to improve the rigour and reliability of findings as well as giving a greater depth of understanding.

3.5.4 Section Summary

An in-depth discussion of these issues, methods and mitigation approaches is discussed in chapter 6.0 and the section on limitations to this research within the thesis conclusions (section 8.4). In summary though, the most appropriate research method would typically include:

- A control group which has no experimental intervention placed upon them;
- A placebo control group which would simulate the teams with an intervention but would in fact contain no useful information;
- A detailed participant selection process, analysis and balancing of the design teams;
- The use of the same design brief for all the experimental groups;
- The control of participant variables, such as design setting, context and experience;
- The avoidance of any bias, either intended or unintended through the participation of the researcher.

3.6 Design Process Evolution

The User-Efficient Design process developed within chapter 7.0 of this thesis was created using a participatory action research (PAR) approach [Avison et al. 1999, Greenwood et al. 1993] and the culmination of several pilot studies. In a participatory research approach the researcher plays an active role with the intended stakeholders in dealing with the research task, rather than being purely an observer [Turnball et al. 1998].

This approach was first introduced by Kurt Lewin in 1946 who believed that an individual's social behaviour was a function of his or her social perceptions. Consequently, the researcher's task was to discover "the meanings actors gave to events while they were acting" [Khanlou et al. 2005] and can involve a whole range of research methods, from quantitative, qualitative, or combined data gathering methods, depending on the issue under investigation.

Currently only a few examples exist where this method has been used in engineering design research, although it is reported to be particularly appropriate for this form of research [Howard et al. 2006, Ottosson 1996, O'Hare 2010]. However the two stage (descriptive and prescriptive) research methodology of Blessing and Chakrabarti [2009] has a lot of similarities.

3.6.1 Key Elements of Participatory Action Research

PAR is considered to be highly relevant for research into design development such as this, because it is only by being an active member of the research that it is possible to witness the small but critical events that lead to significant developments at a later stage [Ottosson 2003, Ottosson et al. 2004]. Since development processes are generally very complex and unique to an organisation, Ottosson records a few findings on using PAR:

- Close and constant interaction is highly important and desired so that information is received straight from the real situation;

- Unspoken important information, which is often difficult to be aware of when using traditional research methods is picked up naturally by the researcher;

- Conducting PAR is more demanding and complex than classical research and requires researchers to have good personal skills, experience and knowledge;

- Research findings can be taken into practical use more quickly for faster feedback.

For these reasons this researcher has decided to adopt a participatory action research approach for the development and evolution of the final design process. The details of this approach are explained in much greater detail in chapter 7.0.

3.7 Chapter Summary

There are five key research activities that contribute towards the overall research program shown in figure 13. This wide ranging scope means that a number of different research methods needed to be employed. For each of these research activities a number of specific methods have been reviewed and described. In particular, the rational for the choice of methods has been articulated. The choice of using non-participant observation, a controlled internal experiment and participatory action research are key to the overall success.

The implementation and results of these methods will be described in the relevant chapter of this thesis and issues relating to the validity of this research are also discussed in detail in the conclusions (chapter 8.0).

The next chapter returns to the research objectives of figure 1 and uses the research method of creating energy models and scenarios to answer the first two questions of research objective two:

1. What are suitable metrics [for measuring energy-using behaviour]?

2. How significant is poor energy-using behaviour?

4.0 Measuring the Energy Losses of Products

In order to quantify the energy impact of inefficient behaviour the terms, as to what is being measured, must first be defined. This chapter will do that and then provide a quick and simple energy model for assessing the total energy efficiency of a product. In this way it is possible to not only calculate the amount of energy wasted by users but also to determine if this should be a design priority for engineers or not. Thus forming an important, and traditionally overlooked, first step in the assessment process of the energy efficiency of products.

A product is designed to perform a certain task and in this case requires an amount of energy to carry out this task. The energy efficiency of that product is a measure of the difference between an ideal theoretical use situation and the reality. The difference is referred to as energy losses and represents the amount of energy wasted through inefficiencies of the product. Traditionally this has only measured the energy losses of the engineering, technical and physical aspects of the product, known in this research as the *intrinsic losses*. However there is a second, often overlooked part, the *user-related losses,* associated with inefficient product use. Unfortunately even the best designed product will waste energy if it is left on or used unnecessarily. The Product Energy Profile (PEP) process, created here, lays out a framework for how user-related losses can be calculated and what percentage of total energy use this represents, displaying this information in a visual format (figure 14).

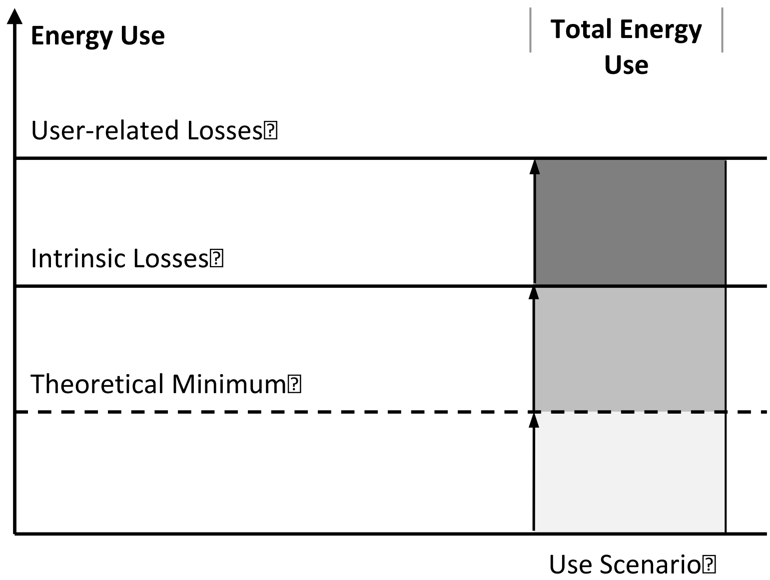


Figure 14 Product Energy Profile (PEP) Model

The following three sections go into greater detail on each of the terms in the PEP Model and the fourth section shows how they can be used with a series of worked examples.

4.1 User-Related Losses

The use of a product will inevitably include a range of good and bad behaviours with good behaviour being more energy-efficient than bad. Empirical studies have shown that energy use can vary by two or three times, even when the equipment used is identical [Gram-Hanssen 2004, Vringer 2005]. The user-related losses represent the amount of energy that has been used over and above the optimal use of a product. For example, the optimal way of using a product such as a kettle or television, is called the base case scenario, from which all other comparisons are made.

The base case is the most efficient way of using a product and hence has zero user-related losses and will change depending on the user's desired outcome from using the product. Consider a kettle, the desired outcome might be boiling enough water for four cups of tea or for a television it could be watching a 45 minute programme. The most efficient way of doing this could be found experimentally and would be called the base case scenario. Any variation from this would show the user-related energy losses.

Since an optimal way of using a product exists, the difference between this base case value and the actual energy use must be attributed to inefficient actions of the user and hence qualify as user-related losses.

In order to calculate what the user-related losses are, first the zero user loss base case scenario is made, based on a specific desired outcome, such as the four cups of tea or 45 minute TV programme. Secondly, comparison scenarios are made, each might be as a result of a different action by the user but with the intention to always end up with the same desired outcome. This will be demonstrated in much greater detail in section 4.4 but, as a brief example here, if the base case for a kettle was to boil four cups of water and the base case did this in one go with no extra water added, a comparison-use scenario might be overfilling the kettle. Therefore the increase in the amount of energy required to boil this larger amount of water is attributed as a user-related loss, since the desired outcome is still four cups of water. The application of these use scenarios quickly demonstrate the impact a particular behaviour or action of the user may have on the product energy-efficiency and a whole range of scenarios can be created. However, it is observational and test data that will determine how frequently these scenarios occur and thus give the full picture of energy efficiency [Elias et al. 2008b].

Many of these use scenarios and the causes of much user-related loss may be the fact that the product has been unintentionally designed in such a way that using it in an optimal way is difficult or inconvenient. This must be addressed as part of the redesign efforts so that the most intuitive way of using a product is also the most energy-efficient [Elias et al. 2007] but the product also creates energy losses of its own independent of any user interaction and these have been called the intrinsic losses.

4.2 Intrinsic Losses

In 1998, a series of tests was carried out on a 200-litre refrigerator, a typical size for a European domestic setting, to determine where the largest sources of energy losses were in the device [Mennink et al. 1998]. The product tested showed losses of 81% due to poor insulation in the walls and door. These losses had not been determined by the way the product is used but were dependent purely on the engineering design and materials of the device and were locked into the product at the point of design and manufacture. They were thus intrinsic to the design and construction of the product. Poor insulation, waste heat, unnecessary movement of parts or any other form of un-optimised technical design can all cause what has been classed here as the intrinsic losses.

Engineers have traditionally focused on these intrinsic losses and have enjoyed considerable success in reducing them with improvements in technology and materials science. For example since 1980, all models of refrigerator and freezer have reduced their energy use by at least 60% when compared to equivalent A+ rated products in 2005 [Rüdenauer et al. 2005].

The Product Energy Profile (PEP) allows engineers and designers to look at the relationship between the user losses and intrinsic losses of a product and decide which is the most important to focus their design efforts on. Thus improving how it is used or improving what is used. For example if the user losses dominate the PEP model then this should attract the most design attention and could be where the easiest gains are made. Although even if the user losses are currently small, they should still receive design attention as this may change over time.

Figure 15 shows how, over the same period of time, the user-related losses as a percentage of the total losses will rise in proportion as the intrinsic losses of the device are reduced with new technology and incremental engineering improvements, assuming that behaviour and thus user-related losses remain the same. For example, if a product today had intrinsic losses of 75% and user related losses of 25% then over time, as the technology improves and transferred to products, the user losses will rise in significance. For this reason, it is worth considering the user-related losses for products where there is a clear improvement programme in place for tackling the intrinsic losses, even if they are currently a small percentage of total energy loss.

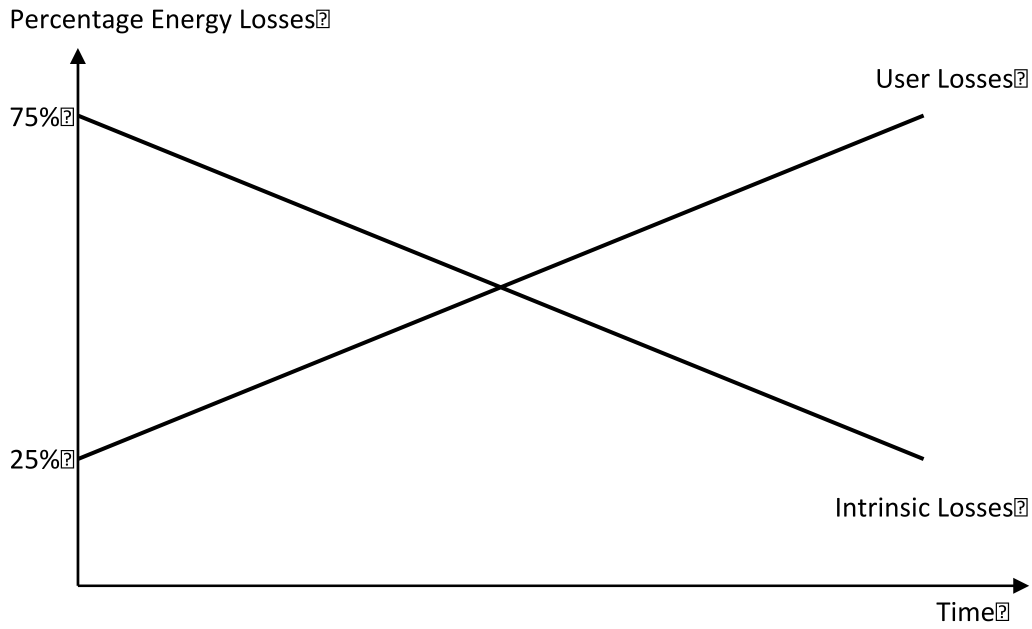


Figure 15: The predicted rise and fall of user and intrinsic losses over time

By taking energy measurements from the product in question, whilst it is being used in the optimal base case scenario, it is easy and quick to identify how much energy is being used by the product. This value is the total energy use of the product in the base case scenario and does not equate to the intrinsic losses.

The total energy use is only of limited use if it is not compared with a theoretical minimum value for the delivered function of the product. Without this minimum value, it is assumed that all energy being used is a loss, or wasted, which is clearly not the case as some benefit to the user is being gained through the use of the product. As a result, the theoretical minimum value, shown in figure 14, is explored in the following section.

4.3 Theoretical Minimum Energy Values

As traditional measures of energy efficiency approach 100%, the intrinsic losses decline to zero and what can be thought of as a theoretical minimum (TM) amount of energy required to perform a given function for that product is reached (figure 16). This is a value below which it is impossible to go due to the laws of physics but it still delivers the desired end result. This concept of a 'desired end result' is important to remember as it determines the theoretical minimum value. In the drying of clothes, for example, there is a range of designs for tumble dryers but to establish the theoretical minimum the comparison must be made between similar contextual situations and products. To continue this example, a comparison cannot be made between a tumble dryer (with perhaps a large TM) and the hanging of clothing on a washing line outside (which it could be argued has a zero TM), since the washing line shares none of the convenience or speed of a tumble dryer, the principal reason for using the device in the first place. In summary essential product features or functions must be kept constant when trying to establish a TM value.

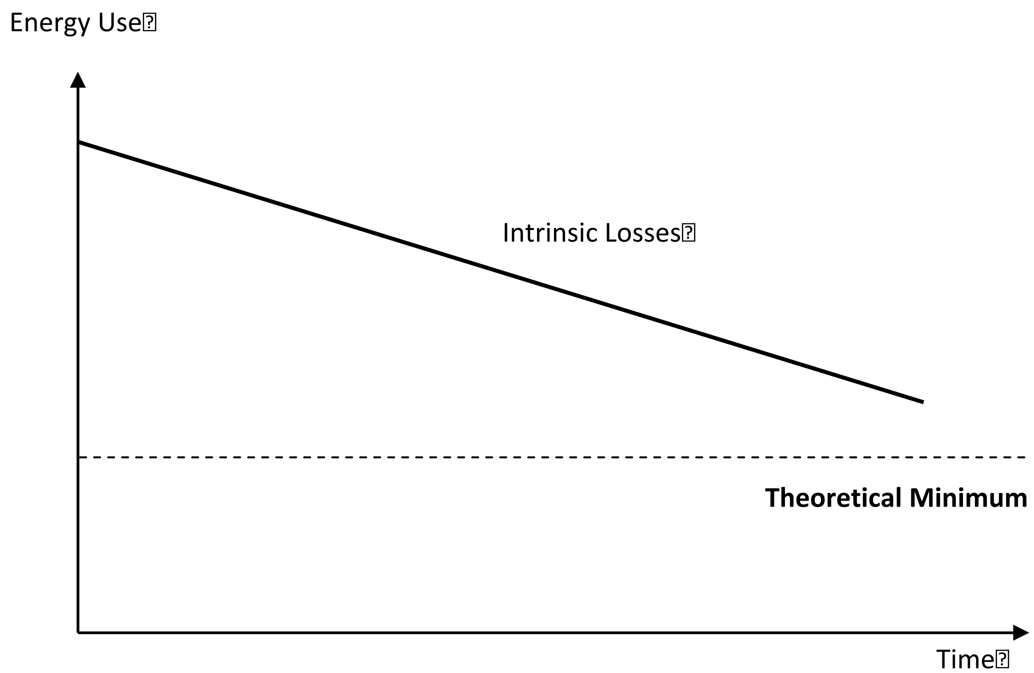


Figure 16 - The decline of intrinsic energy losses over time due to improved technical design

For some products, such as a kettle, this may be an easy value to calculate. The laws of thermodynamics can easily give a value for the energy required to raise the temperature of water to 100 ^{o}C. However, for other more complex products this is more difficult and perhaps impossible. The amount of energy required to create a moving image on a screen and all the associated controls and sound generation make calculating the TM for a television very difficult.

Establishing a TM for a television and other more complex products can be done in a different way. First, the most efficient product in that class must be found: one which adheres to all the requirements of the product being examined, such as screen size, image quality and colour etc. The energy value for running this product is then set as a benchmark and compared to reports on the future energy-efficiency improvement potential for this technology. Coupling the most energy-efficient current product in its class with the combined future improvement potential for this technology will therefore give a good estimate of the theoretical minimum.

In order to determine the losses and efficiencies of a product, this theoretical base case or minimum value must be created. The difference between this minimum value and the actual energy readings highlight the intrinsic losses of the product. Any variation on the part of the user which prevents the product from performing the most efficient course of action is attributed to user-related losses. Due to the variation in use, product-use studies must be undertaken with the results being developed into behaviour scenarios where each scenario shows a different energy-*inefficient* use of the product. The probability of each scenario occurring is established as well as its energy impact. Those quantified scenarios can then be used to prioritise the redesign efforts.

To demonstrate this loss-calculating process, three worked examples are presented below to show how a theoretical minimum value is established and how intrinsic losses and user-related losses are compared.

4.4 Product Energy Profile Worked Examples

A true measure of energy efficiency is based on the combination of intrinsic and user losses. The inclusion of user losses, from the use and possible misuse of a product, adds a new dimension to the traditional measure of engineering energy-efficiency calculations, giving a more complete image of product efficiency. In order to obtain this new measure certain information is required (figure 17).

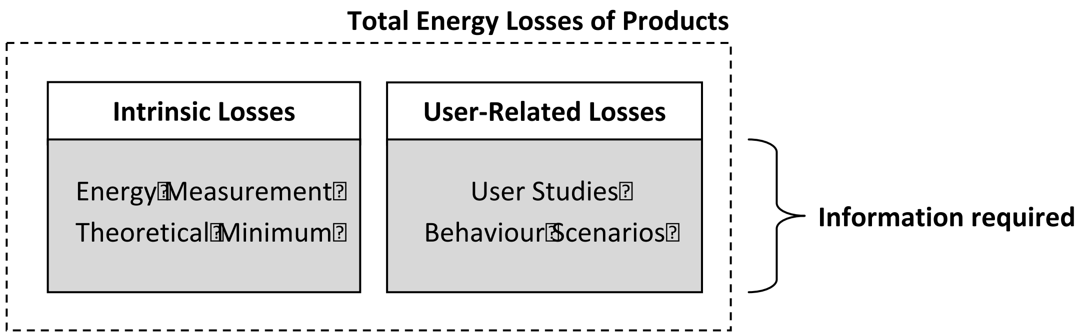


Figure 17 - A picture of total energy losses for a product and the information required to calculate them

Three case-study products have been chosen as worked examples because of their significance as high-energy users in a typical domestic home but also because they will show a range of calculation techniques, the aim being to clarify the concepts involved. For these examples, two fictitious user-behaviour scenarios will be created using some quick and basic-use studies. The first, Scenario A will represent a minor and perhaps typical inefficient behaviour, whilst the second, Scenario B, will be more alarmist in its nature.

4.4.1 First Example: A Domestic Kettle

The kettle is a simple example to begin with. Its theoretical minimum can easily be calculated and most readers will have experienced many of its potential bad-use scenarios. The starting point of the process is to establish or declare the base case scenario, which is the desired outcome and the perfect-use scenario. In this case, the outcome is the boiling of one litre of water, the equivalent of four cups, to be used for hot drinks. Table 3 shows test data for a 2.8 kW kettle, using water with a starting temperature of 10°C, giving the amount of water being boiled, boiling times and energy usage.

To enable a comparison, the recorded boiling times have been simplified and rounded up to the nearest 30-second denomination and it is these times that have been used for all subsequent calculations. The data in table 3 suggests that there is an initial amount of energy required, regardless of the volume being boiled (approximately 30 seconds or 0.023 kWh). It also shows that a linear relationship develops between the amount of water being boiled and the time take to boil it (30 seconds for every 250 ml). Therefore it follows that the most efficient way of boiling one litre of water is in a single go, as boiling it in four lots of 250ml will use approximately 60% more energy (0.117 kWh over 0.188 kWh, which is 4 x 0.047 kWh).

Volume of Water (ml)	Recorded Boiling Time (seconds)	Simplified Boiling Time (seconds)	Energy Used (kWh)
250	53	60	0.047
500	88	90	0.070
750	112	120	0.093
1000	140	150	0.117
1250	168	180	0.140

Table 3 - Kettle (2.8 kW) boiling test data [taken from Elias et al. 2009]

Theoretical Minimum

To raise the temperature of one litre of water to 100^{o}C, based on the specific heat capacity of water (4186 Joules / kg ^{o}C) and a starting temperature of 10^{o}C requires 377,100 Joules of energy, or the equivalent of 0.105 kWh. The sample kettle took 2.5 minutes to boil a litre of water using 0.117 kWh (421,200 Joules). The intrinsic losses, when boiling the litre of water in a single go, are therefore the difference between the two or 0.012 kWh (43,200 Joules) with an intrinsic inefficiency of 10% (the difference 0.012 / 0.117 = 10%), meaning that 10% of the energy required to boil water in this kettle is surplus to the theoretical requirements. This is shown as the base case in figure 18 but can change depending on how the kettle is used, as shown in Scenario B.

Behaviour Scenarios

A standard kettle is easy to use and easy to use badly, as many kettles do not have accurate systems for filling and require an element of pre-thought and planning in order to be used efficiently. For this example two scenarios have been generated, which consider the tendency of users to use a kettle in an energy-inefficient manner by boiling more water than is required.

Scenario A: The same kettle described previously is used to boil four cups of water, totalling one litre. However due to inaccurate, inconvenient or even non-existent capacity measurement on the device, the kettle is overfilled by

25% and is boiled once for all four cups, resulting in an excess amount of water being boiled. In effect 1250ml of water is boiled, using 0.140 kWh (504,000 Joules), a user-related loss of 0.023 kWh (82,800 Joules).

Scenario B: Over the course of a day, the same sample kettle described previously is used to produce two cups of water (250ml each) on two occasions, once in the morning and once in the evening, totalling one litre. However, in this scenario, the kettle is filled to its one litre capacity in the morning and boiled once full (1000ml) in the morning and once half full (500ml) in the evening. Using the data from table 3 the kettle would use an additional 0.047 kWh (169,200 Joules). In total 0.187 kWh (673,200 Joules) of electricity was used to perform a task that would require 0.14 kWh (504,000 Joules) for this kettle. An increase of 34% which is split between the new intrinsic losses (0.035 kWh, because boiling 500ml in the kettle twice, uses more energy than boiling it once with 1000ml) and the user losses (0.047 kWh, the wasted energy from the unnecessary boiling of the extra 500ml on the first occasion).

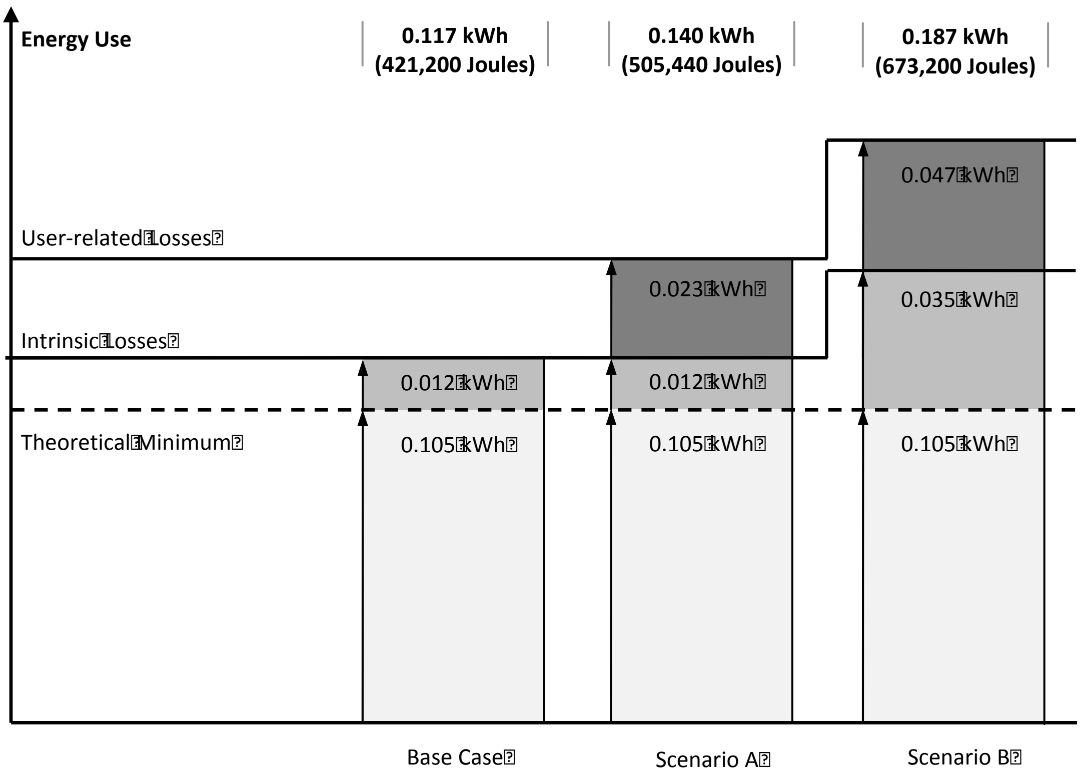


Figure 18 - Product Energy Profile (PEP) for a Domestic Kettle per day

Discussion

The results from figure 18 show how the user-related and intrinsic losses for this product can change considerably compared to the theoretical minimum. Suggesting that the focus of re-design efforts should be split between both kinds of losses.

The test data (table 3) shows much higher intrinsic losses for boiling smaller amounts of water and in fact suggests that, if the user is uncertain about how much water they require it is always better to boil more than boil an additional smaller amount later. This is clearly not a desirable feature of the product. Ideally, a proportional relationship is required whereby the percentage of intrinsic losses is constant. Thus allowing users to be as precise as possible, with no penalties for using less and topping up, rather than over filling “just in case” and being wasteful.

There are currently two products that may address this issue. The first is a ‘kettle replacement product’, designed for a coffee drinking market, which uses a through water element, only heating water when it is leaving the product. The standard model provides a fixed amount of hot water per activation (220ml). However a version exists that allows the user to vary how much water is heated. Experimental evidence shows that this product generates a cup of 220ml of water at 85^{o}C in approximately 30 seconds, using an estimated 0.023 kWh (84,000 Joules). A second product worth mentioning here is a ‘boiling water on demand’ tap which is a kitchen tap that provides boiling water whenever needed. With a three-litre-capacity insulated tank, this product keeps water at a constant near boiling temperature using 0.24 kWh (864,000 Joules) per day in a standby heating mode to maintain this temperature. A high user of small quantities of boiling water would benefit from this product. However this product has an obvious rebound effect as the increased convenience this product offers may result in a much greater usage of boiled water than previously. The rebound effects of this product would therefore be large, negating any energy saving and in fact increasing its energy use beyond previous levels.

4.4.2 Second Example: An LCD Television

The second worked example is a more complex one. Consider a modern 32” LCD flat screen television, using 150W to run. The theoretical minimum for a product such as this is much harder to calculate compared to the simplicity of a kettle and so a different approach is required. The size of the unit as a whole and the screen size are important features that must be preserved across any comparison and for this reason a theoretical minimum must be found that uses flat screen technology and a 32" screen.

Table 4, taken from an EU sponsored research report looking into a technology assessment of modern televisions as part of the EuP Directive preliminary reports [EuP Preparatory Studies 2007], shows potential technology currently under development and a rough guide to their energy improvement potential for a 32" LCD television. Most of the improvements relate to the Back Light Unit (BLU) and any mutually exclusive improvements that cannot be implemented simultaneously have been removed from the table so as not to be double counted. Totalling the improvement potential from this table gives a minimum improvement potential of approximately 65%.

Therefore, it can be assumed that the 150 W television under investigation has a practical theoretical minimum of approximately 52.5 W and subsequently intrinsic losses of 97.5 W (65% of 150 W). For the purpose of these calculations it is assumed that standby power consumption is one watt, however many new televisions of this type use considerably less.

Option	Specification of improvement	Improvement potential	Cost factor / availability
BLU driver / inverter circuitry improvement	Advanced BLU driver / inverter circuitry with electrical efficiency of η 80 to 85%.	Good 5-10% improvement	Cost neutral electronic components and board design (cost trade-off possible)
LED-BLU	Very new – not yet mature – BLU type allegedly very high power saving potential due to low power requirements and capability of image controlled selective dimming. No known hazardous substances (however, material composition diverse, manufacturing and electronic packaging unknown).	Excellent >25% improvement	Cost increase currently very limited availability, could improve with mass application within next five years, IP issues unknown
LCD panel design	General improvement of optical properties of functional layers, color filter and pixel design (e.g. RGB + White pixel), electrical driving scheme resulting in higher light utilization. This in turn can reduce the number of necessary lamps and power consumption accordingly.	Unknown	Unknown proprietary technology
Efficient polarizer / fewer lamps	Reflective polarizer (e.g. marketed by 3M) or prismatic film achieves a higher utilization of the lamp's randomly emitted light. This in turn can reduce the number of necessary lamps and power consumption accordingly.	Excellent >25% improvement	Cost increase proprietary technology
Direct power supply for BLU	Direct power conversion from mains input to BLU. Avoid lower voltage intermediate steps. Very good potential for electrical efficiency improvement.	Very Good 10-25% improvement	Unknown BLU supplier relation issues, power board design

Table 4 - LCD television potential technology improvement [adapted from the EuP Preparatory Studies 2007]

The base case for this Product Energy Profile (PEP) (figure 20) is the UK's average of 3.6 hours of watching television per day with no standby time. Again two scenarios have been created which present typical uses of the television from which the user-related losses can be found.

Scenario A: In this scenario the television is on for an additional hour per day (4.6 hours) but is not being watched or used in any beneficial sense, therefore wasting the full 150 W (0.15 kWh) for the additional hour. This could occur when users who are watching television may then leave the room to prepare a meal or do some other activity only to return later to watch a following program. In addition to this the television is left on standby for the remaining 19.4 hours of the day (0.019 kWh with standby consumption assumed to be one watt an hour). Thus resulting in an increase of 0.169 kWh over the base case.

Scenario B: This scenario may be more typical of people or children with televisions in their bedrooms and is that of the user falling asleep with the television on, waking several hours later to find the television still on and turns it off. This would create considerable user-related losses and is probably not a daily occurrence for most users. For this particular scenario information was used from a 15-week study, undertaken by this researcher, in which the on/off times of a user's television was monitored (table 5 and figure 19) showing the average on time per day of 6 hours, an increase of 2.4 hours (0.36 kWh) over the base case. This study found that such a scenario happened up to 14 times over the 15-week period.

Total time monitored:	2520 hours
Total on time:	631 hours (25%)
Average on time per viewing:	1.87 hours
Average on time per day:	6 hours
Longest on time:	16.77 hours

Table 5 - Television on/off data over a 15-week period

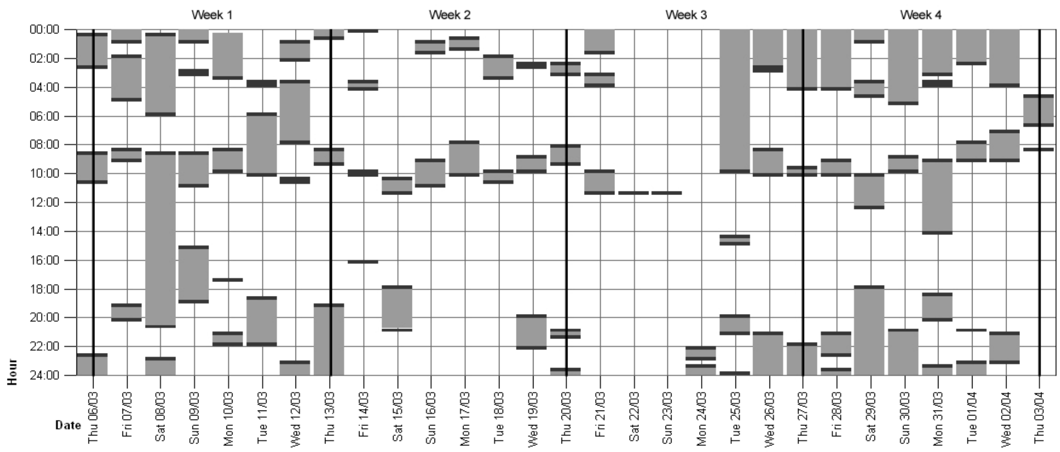


Figure 19 - A sample four week section of time log data from a television

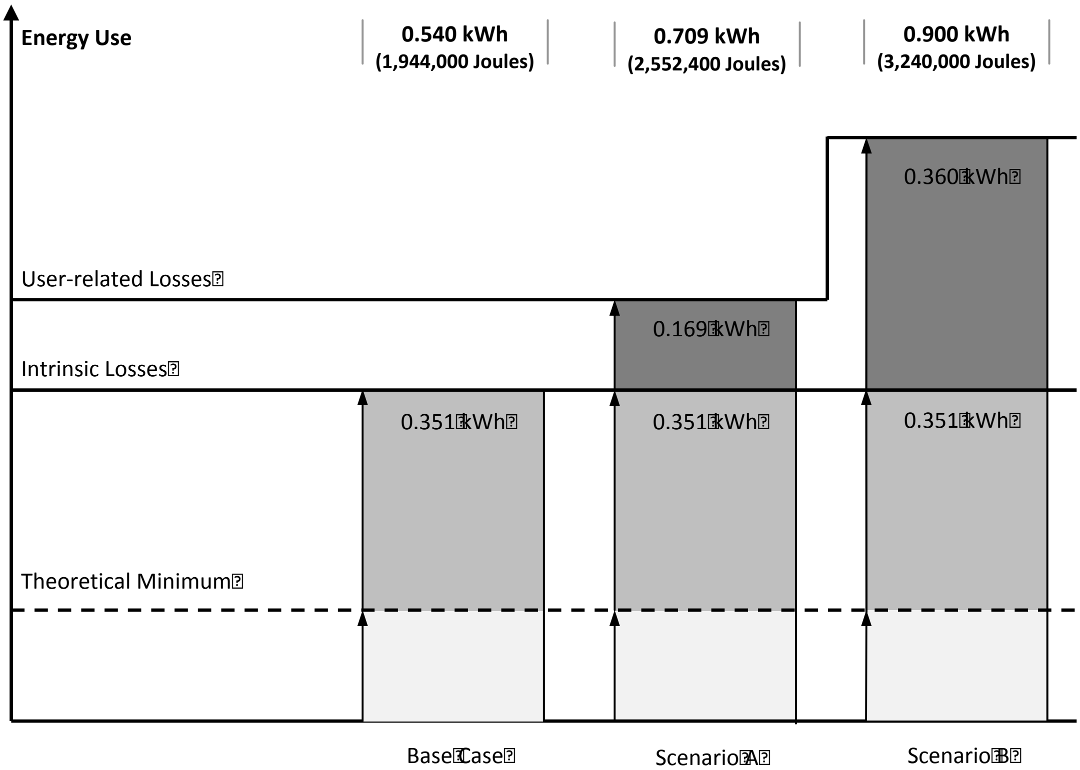


Figure 20 - Product Energy Profile (PEP) for a 32" LCD Television per day

The probability of a scenario occurring highlights the next important stage of the PEP. Once a whole range of scenarios have been created, it is important to establish how often these scenarios happen. It would be an alarmist strategy to create a high impact scenario with overwhelming user-related losses and ignore the fact that it has never yet been witnessed or happens only rarely.

Discussion

The television has a more evenly spread energy profile (figure 20) with 65% of the base case being intrinsic losses, compared with just 10% for the kettle. With such a high energy using product, inefficient behaviour has a dramatic impact on energy use, rising by 31% in Scenario A with the addition of a single extra hour worth of on time and over 19 hours of standby use. In Scenario B the user losses raise the total energy use of the product by two thirds, from the base case, and as can be seen from the test data of table 5, this is perhaps not an unlikely scenario.

A study in 2005 investigated how 10 participants used appliances around the home; in particular for how long the television was used and if anyone was watching it at the time [Rodriguez et al. 2005]. The results showed that 90% of participants left the television on only to hear the sound, with times ranging from 5 minutes to over an hour a day. They go on to discuss the idea of a "blind" mode for the television where if no one is watching, it could automatically dim or even turn off the screen. This makes good sense as even an energy-efficient television uses 8 - 10 times more electricity than a radio.

4.4.3 Third Example: A Domestic Refrigerator

The third and final worked example shown here is that of a typical domestic, single door, 200-litre refrigerator, using 250 kWh a year. A refrigerator works by compressing a gas into a liquid state. As the liquid gas is allowed to expand and evaporate it becomes very cold. The cold gas moves through coils at the back of the device and draws heat from the contents of the refrigerator, reducing the temperature of the air and contents inside the refrigerator. Opening the door and allowing the contents to warm therefore causes more energy to be used as more gas needs to be compressed.

The energy data for this example has been taken from two refrigerator studies. The first, by Mennink et al. [1998], calculated 81% (202.5 kWh) of the energy used was lost due to the insulation of the door and walls, 11% (27.5 kWh) from the addition of food (taken to be 4kg a day) and 8% (20 kWh) from door openings, 24 times a day for 5 seconds each (equating to 2 minutes open time a day and an energy value of 0.46 Wh per second open). The second, by Saidur et al. [2002] found an energy impact of 9 Wh - 12.4 Wh per 12 second door opening (equating to an energy value of between 0.75 - 1.03 Wh per second open), which is also supported by a third study [Parker et al. 1993] who calculated an impact of 9Wh per opening. An average value of 0.68 Wh per second open will therefore be used as an average of these studies (additional research and material can be found in Research Appendix 9.2.7).

The theoretical minimum for this product is, like the television, also difficult to calculate. In Mennink et al.'s [1998] refrigerator study, they conclude that a refrigerator using less than 50 kWh a year is feasible. Thermodynamic analysis of cooling 4kg of food (assumed to be the equivalent of 4 litres of water) every day from room temperature of 21 ^{o}C to a temperature of 5 ^{o}C suggests an energy requirement of 27.16 kWh per year. A compromise between the two of 39 kWh per year (or 0.107 kWh per day) could therefore be a reasonable assumption.

Behaviour Scenarios

The base cases for all three product examples discussed in this paper, although showing no user-related losses, have included an element of user interaction in the intrinsic losses. This is a fundamental assumption of the base case, as without any user interaction the product would not be being used at all. For the kettle, it was the requirement to boil one litre of water and for the television a watching time of 3.6 hours was included. The refrigerator is no different and for this base case it includes two minutes' worth of opening time per day. Therefore, the intrinsic losses will be the total energy use minus the theoretical minimum and divided by the number of days in a year for a daily figure (250 kWh – 39 kWh / 365 days = 0.578 kWh per day).

Scenario A: The door is opened for an additional two minutes in the day, due to time required to think about and search for what food is required, a common occurrence in the use of cold appliances [Elias et al. 2008a, Tang 2008b], creating user-related energy losses of 0.082 kWh.

Scenario B: This scenario uses information from a video study of a young family using their kitchen and refrigerator for making breakfast [Tang 2008b]. In this study the refrigerator was opened a total of 21 times and on three occasions the refrigerator was left open for a total of 191 seconds. If this situation were repeated in the evening, the refrigerator would have been opened 42 times (at 5 seconds a time) with an additional 382 seconds for the six extended open periods, totalling 592 seconds open, creating user-related losses of 0.403 kWh over the day.

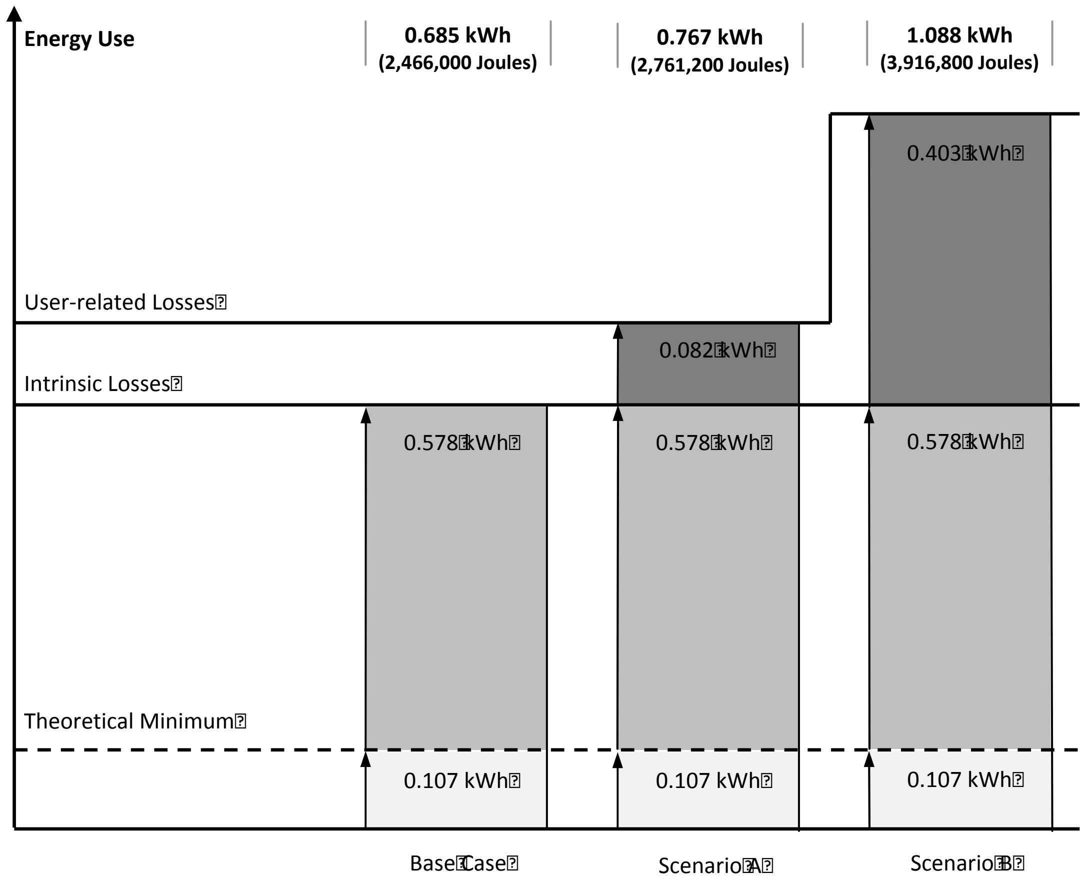


Figure 21 - Product Energy Profile (PEP) for a 200-litre domestic refrigerator per day

Discussion

Figure 21 shows the PEP for a typical 200-litre refrigerator and the impacts of some common behaviours in relation to the total energy use. This product, in scenario A, is dominated by considerable intrinsic losses caused mainly by poor insulation. Doubling the time the door is open represents a 10% increase of the energy used by the product, a relatively insignificant amount when compared to the intrinsic losses and in line with the other refrigerator studies. Scenario B however represents a much higher usage with 37% attributed to the user's actions. Thus exceeding the daily energy use of the heavily used television from figure 20, and almost equalling the intrinsic losses. Scenario B must surely be a rare case, totalling almost 10 minutes of refrigerator open time a day.

Comparing the PEPs of different products provides an interesting picture as to their relative energy use and raises a point about the ease with which energy might be saved from one product only to be wasted by inefficient behaviour in another. Awareness among users of the energy impact of products is commonly discussed in literature on this subject [Mansouri et al. 1996] and some products do not make it clear to the user that they are wasting energy. For example the user is only aware that the kettle has wasted energy after they have poured the required amount of boiled water and discovered water remaining. The physical state and appearance of the refrigerator does not change when the door is open to when it is closed. There is perhaps a great deal of scope available to changing the way products react to how they are used, encouraging or even forcing efficient behaviour.

4.5 Chapter Summary

In summary the Product Energy Profile (PEP) approach demonstrates a modelling method for showing the significance of user-related losses as a proportion of total product energy use, addressing research questions RQ 2.1 and RQ 2.2. User-related losses are likely to grow as a percentage of energy loss as engineers have tended to focus on the intrinsic losses, driving them closer to the theoretical minimum.

Up until this point, what has been missing from research into design-led behaviour change is a way of identifying the relative importance of these user losses compared to the total energy use of the product and whether any designed improvement would actually provide a net gain in efficiency. The Product Energy Profile framework presented here aims to fill this gap, providing a modelling method for quantifying the energy efficiencies of product use, from the energy required to deliver the desired function to the amount of energy wasted through careless actions.

The development of a technical framework for predicting, measuring and analysing the energy losses of products has been presented and the real-life data for this can now be gathered. Real-life observation studies and data collection techniques will give a more accurate judgement as to the likelihood of an action or behaviour scenario occurring. Thus the next chapter tackles the final research question from research objective two by developing and trialling a user-centred method for investigating, recording and quantifying the energy-using behaviours of users in a kitchen.

Research Questions (RQ)		Research Activity	Chapter

Objective 1: To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour

RQ 1.1	What is poor energy-using behaviour?	Literature Review	2.0
RQ 1.2	How can it be changed?		
RQ 1.3	Can behaviour change be designed?		

Answered

Objective 2: To create a way of measuring the energy impact of user's behaviour

RQ 2.1	What are suitable metrics?	Energy Modelling	4.0
RQ 2.2	How significant is poor energy-using behaviour?	Use Scenarios	
RQ 2.3	How can information on behaviour be collected and turned into useful data?	Observational Studies	5.0

Answered

Objective 3: To explore how designers might use information on behaviour to design

RQ 3.1	How can this information be used to aid the design of products?	Literature Review	6.0
RQ 3.2	How do designers interact with this information?	Design Experiment	
RQ 3.3	How should this information be presented?		
RQ 3.4	What impact will it have on the design output?		

Objective 4: To investigate if it is possible to design products so that they can only be used in an energy-efficient manner

RQ 4.1	What would such a design process look like?	Participatory Research Design Process Demonstrator Industrial Consultation	7.0
RQ 4.2	Can a product improve the impact of poor energy-using behaviour?	Product Demonstrator	

Research Progression and Chapter Outline

5.0 Studying the User

For this research the author chose to conduct a series of in-depth user studies in two different kitchens using non-participant video techniques (section 3.4). Following from an exhaustive and highly time-consuming first study (Study A) the products under investigation were narrowed down to just the refrigerator, but it was still important to view the actions of the entire kitchen so that the context of the refrigerator's use could be established. From this context it is possible to understand a human motive to each particular action rather than just the physical operations it involved.

This study drew humorous comparisons with Bent Hamer's 2003 film "Kitchen Stories", figure 22, when a mock team of Swedish researchers from the fictitious Home Research Institute arrive in a rural area of Norway to observe the kitchen routines of single men. Perched on his observation chair in the corner of the kitchen, Swedish researcher Nilsson attempts to record all the behaviours of his reluctant single man, only to discover he is himself being spied on through a hole in the ceiling!

Figure 22 - A screenshot from Bent Hamer's 2003 film "Kitchen Stories"

Figure 22 shows a screenshot from Bent Hamer's film, with Nilsson watching closely from his corner viewpoint. Unlike Nilsson however, this researcher chose not to be physically present in the study as this may influence the results, as Nilsson found. Instead, motion-detection video cameras were used to record precisely the residents' actions and movements in their kitchen. The footage was then replayed at a later date with the individual actions and corresponding times recorded. Study A (kitchen shown in figure 23) recorded the daily use of all energy-using products in the kitchen of a shared residence of four young adults for nine days. The camera was present for at least 30 days before filming commenced, in order that the residents might normalise to its existence and not be influenced by 'acting' for the camera. This first study was interested in examining the residents' actions and behaviours with every energy-using product in the kitchen, but this was later reduced to just the refrigerator for the second study.

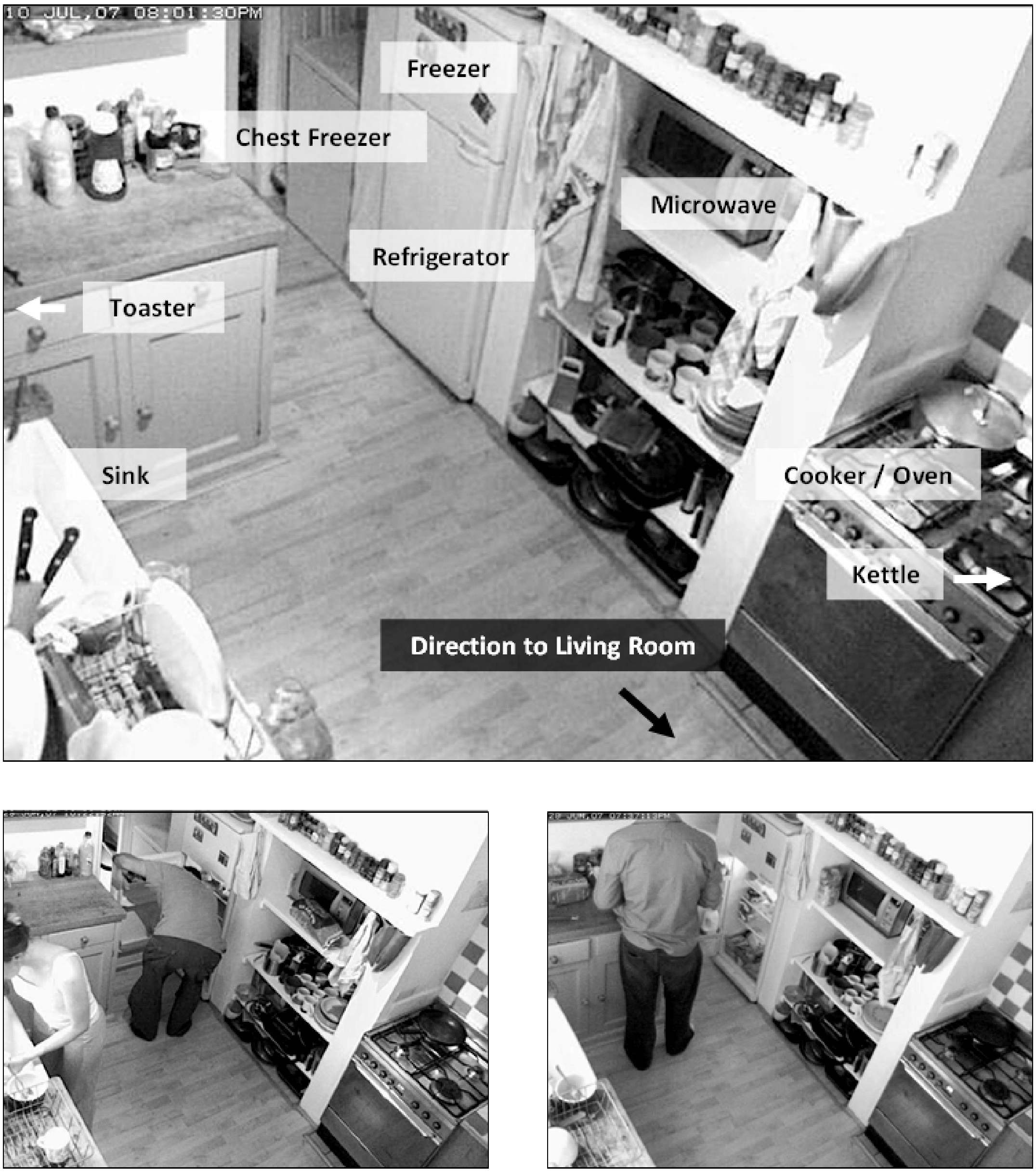


Figure 23 - Study A: Nine Days, a shared residence of four adults

In study B (kitchen shown in figure 24) the camera recorded for 18 days in the home of a couple with a young child. On this occasion the camera was installed and began recording immediately as no time was available for resident familiarisation. Figures 23 and 24 show the camera angle used. In both the refrigerator is central to the picture with other appliances and useful landmarks labelled.

Figure 24 - Study B: 18 Days, two adults and a young child

The house in Study A was the researcher's own home, and chosen not only because of the practical limitations of finding volunteers for such a study, but also because the high occupancy level of four adults made it likely that a high variety of different behaviours would be recorded in the same environment from a single camera. It was also simple to run as a pilot study to ensure all equipment and processes were working satisfactorily before a second study was undertaken. The house in Study B was chosen next because it offered a different demographic to the first study, with the possibility that the young child may provide new and previously unobserved behaviours, applicable to families. The video footage from both studies shows several people performing their daily activities with an often high level of interaction with many products in the kitchen. However, as was described at the start of this chapter, the first study (Study A) investigated the users' behaviour of every product in the kitchen. This proved to take a considerable amount of time and the decision was taken to narrow down the investigation to just a single product, the refrigerator. The justification for this selection is described in the following section.

5.1 Product Selection: The Domestic Refrigerator

The refrigerator and other cold goods are often the highest energy-using products in the home, accounting for 22% of the total domestic electricity use in the UK, second only to lighting at 23% [DTI 2002], and in 1995 were the largest end-users of electricity in US homes, accounting for 7% of electricity [Meier 1995]. However as Mansouri et al. [1996] discovered they are generally not thought of by the users to be high energy-using products at all, making them ideal candidates for design for behaviour change studies.

Worldwide the refrigerator has been the subject of extensive research. Table 6 shows a summary of 47 different research studies from around the world, looking at almost all aspects of refrigerator-use and energy-impact. Most of the published documents and studies included in this table are cited in three literature reviews. First, a large review by James et al. [2008], which looked at operating temperatures and subsequent food hygiene levels. Second, an 'Energy Using Products" review document [Stamminger et al. 2007], written for the European Commission into consumer behaviour, looked briefly at almost all aspects of energy use. Lastly, a smaller review by Saidur et al. [2002] and a collection of independent studies tended to focus on door openings.

In broad terms the focus of these studies fall into the following six categories: 1. Operating Temperature and Thermostat Controls; 2. Insertion of Food and Liquids; 3. Surrounding Ambient Temperature and Refrigerator Location; 4. Thermal Efficiency of the Refrigerator Structure; 5. Door Openings and 6. User Behaviour.

Categories:	1		2		3			4	5			6	
	Operating Temperatures	Energy Impact of Operating Temperature	Temperature Changes due to the Insertion of Food	Energy Impact of the Insertion of Foods	Energy Impact of Room Temperature	Location within the Home	Energy Impact of its Location	Energy Impact of Different Components	Frequency of Door Openings	Door Opening Time	Energy Impact of Door Openings	User Behaviour	Energy Impact of User Behaviour
James et al. (2008)	●		●										
ARS (2004)	●												
Azevedo et al. (2005)	●												
Bakalis et al. (2003)	●												
Breen et al. (2006)	●												
Daniels (1998)	●												
Evans et al. (1991)	●												
Flynn et al. (1992)	●												
Ghebrehewet et al. (2003)	●												
Johnson et al. (1998)	●												
Kennedy et al. (2005)	●												
Laguerre et al. (2002)	●												
Laguerre et al. (2004)			●										
Lezenne Coulander de (1994)	●												
O'Brien (1997)	●												
Rose et al. (1990)	●												
Sergelidis et al. (1997)	●												
Sun et al. (2005)			●										
Taoukis et al. (2005)	●												
Terpstra et al. (2005)	●												
Van Garde et al. (1987)	●												
Victoria (1993)	●												
Worsfold et al. (1997)	●												
EuP Review Document (Stamminger et al. 2007)													
Bohmer et al. (1998)		●		●	●						●		
Flynn et al. (1992)	●												
HMWVL (2005)					●								
James et al. (1992)a	●				●	●							
James et al. (1992)b											●		
Laguerre et al. (2002)	●					●			●				
Lepthien (2000)		●		●	●		●				●		
O'Brien (1997)	●					●							
Peart (1993)					●						●		
Rahman et al. (2005)	●					●			●				
Spriegel (1991)	●												
Stiftung Warentest (1994)					●								
Saidur et al. (2002)		●			●						●		
Alissi (1987)											●		
ASHRAE (1988)								●					
Gimes et al. (1977)		●									●		
Meier et al. (1993)					●								
Parker et al. (1993)									●		●		
Meier (1995)		●							●		●		
ELIMA (2005)										●			
Mennink et al. (1998)								●			●		
Tang et al. (2008)									●	●		●	
Elias et al. (2007-2009)									●	●		●	●

Table 6 - Refrigerator Literature and Research Summary

It is important to note, when considering table 6, that as it was not always possible to obtain the original documents which were cited in the review papers, some of the results discussed here rely on the citations being accurate. Where it has been possible to obtain the original documents, these are referenced. In the cases where this has not been possible, the author that cites them is referenced. Throughout the remainder of this thesis data and results from this literature review may be called upon, a detailed review of which is available in Research Appendix 9.2 if additional clarity is required.

In summary, a great deal of research has already been carried out on refrigerators. However, there is only one other research project [Tang et al. 2008] in this specific area of user behaviour and refrigerators and this was limited in its scope to a qualitative assessment and a few overall time measurements. The large body of technical work, lack of behaviour research, ease of user observation and low cost of alteration make the domestic refrigerator a perfect subject for quantified behaviour studies, subsequent redesign and prototyping.

5.2 Data Collection

With a decision made as to which product to study, the actions of the kitchen users could be logged in a time chart with a description of the activity and who was performing the action. It included all users, including temporary visitors to the kitchen such as household guests and domestic staff. An example section of this log, from study A, is shown in table 7. The video log is organised into actions, each with a start time, person involved and the action. For a refrigerator, a key factor in its energy use is the length of time the door is open. The data within this log allows analysis to be made of how long particular actions took, in what order things were done and how different individuals performed the same task differently. The purpose of this analysis is to identify which are the most energy intensive behaviours, so that future product designs can address these issues as a priority.

In analysing the data from table 7 note the opening and closing times of the refrigerator. These tend to frame a particular event as the research found that it was common for only a single action to be performed every time the door was opened. By recording these times, an accurate value for the time taken to perform the action can be obtained. On occasions where a series of actions were performed, a judgement is made as to when the first finished and the second started. This can be difficult if the user is partially or completely blocking the view of the camera.

This raw data can now be converted into times and frequencies for particular behaviours. The list of behaviours is described in the following section and was created before the studies were undertaken and was amended or altered as the video was analysed.

Date	Time	Person	Action
06.5.08 (Tuesday)	19:26:32	A	Opens Fridge
		A	Takes milk from Fridge
	19:26:35	A	Closes Fridge
	19:27:07	A	Opens Fridge
		C	Puts milk in Fridge
	19:27:14	C	Closes Fridge
	19:27:50	A	Opens Fridge
		A	Takes something from Fridge
	19:28:03	A	Closes Fridge
	19:35:04	B	Opens Fridge
		B	Takes vegetables from Fridge
	19:35:15	B	Walks away
	19:35:20	B	Returns
		B	Takes vegetables from Fridge
	19:35:29	B	Closes Fridge
	19:36:02	B	Opens Fridge
		B	Looks for something in bottom drawers
	19:36:07	B	Closes Fridge
	19:51:08	B	Opens Fridge
		B	Searches Fridge and takes something
	19:51:22	B	Closes Fridge
	19:51:25	B	Opens Fridge
		B	Takes something from Fridge
	19:51:28	B	Closes Fridge

Table 7 - Video Action Time Log, an example section from Study A

5.2.1 Data Coding

The first step when analysing the data is to create a list of all the possible ways the product, in this case a refrigerator, could have been used, i.e. a list of possible behaviours. In essence these are the behaviour scenarios from section 4.4 (Product Energy Profile worked examples). The observed behaviours can then be tallied against this list, grouped and counted. This list was created through a combination of brainstorming before the studies took place and changing or adjusting this as the studies were analysed.

A critical aspect of this process is the separation of the behaviour into an *action,* a simple physical task such as "open door" or "fill kettle", and a *motive,* the why, "to look inside" or "to boil water for cooking". For the refrigerator the user interaction tends to revolve around the opening and closing of the door, but the combination of action and motive gives much greater depth of understanding into the same simple physical activities. This is an important distinction, as for a simple product, such as the refrigerator, there are very few different physical actions, but a range of different reasons or motives. The motive captures the context of the action and thus is essential to understanding the behaviour.

Table 8 shows 16 possible scenarios for use of a domestic refrigerator, grouped under actions and then motives. These scenarios can now be matched to the video time log. Behaviours 1 - 10 are all initiated by the action of opening the door in order to do something and end when the door is closed or when a second action begins. Behaviours 11 - 16 are specific to actions that are related to the door already being open. Some of the 16 behaviours were more frequent in one study than the other and some did not appear at all. When the reason for opening or leaving the door open could not be deduced from the video, it would be classed as an unknown behaviour. The list is not exhaustive and further studies might reveal more behaviours that were previously not thought of or witnessed which can be added to the results and inform future design decisions.

Action	Motive	No.
Open door in order to	Look / Search / Sort inside	1
	Take something	2
	Load something	3
	Load something hot	4
	Load shopping	5
	Use something in refrigerator	6
	Play with / Boredom	7
	Clean	8
	Immediately close	9
	Unknown	10
Leave door open because	Doing something with removed item	11
	Distracted / Doing something non-related	12
	Put things back that have fallen out	13
	Not closed properly	14
	Use as a light	15
	Unknown	16

Table 8 - Refrigerator behaviour scenarios divided into action and motive

By going through the Video Action Logs for both studies and attributing to each observed behaviour an action and motive from table 8, a researcher can begin to quantify which behaviours, from the list of all that are possible, are significant and on which a design team should focus.

5.2.2 Study Results

As can be seen from the results of table 9, there is considerable variation between the two households. Despite half the number of adult occupants taking part in Study B compared to Study A, the average total open time for the refrigerator per day in Study B is more than twice that in Study A, at almost five and a half minutes per day compared to only two and a half.

	Study A (9 Days)			Study B (18 Days)		
Behaviour Description	**Time (seconds)**	**Frequency**	**Average Time**	**Time (seconds)**	**Frequency**	**Average Time**
Open door in order to...						
Look / Search / Sort inside	301	21	14.3	993	99	10
Take Something	464	66	7	2353	298	7.9
Load Something	296	66	4.5	1662	301	5.5
Load Shopping	20	1	20	212	10	21.2
Use Something in Refrigerator				55	3	18.3
Play With				46	2	23
Clean				95	2	47.5
Immediately close				12	4	3
Door left open because...						
Doing something with a removed item	169	7	24.1	215	31	6.9
Doing something not related to fridge	81	1	81	187	20	9.4
Putting things back that have fallen				49	7	7
Not closed properly	7	1	7	16	2	8

	Study A (9 Days)	Study B (18 Days)
Total time door open (seconds)	**1338**	**5895**
Average total time door is open per day (seconds)	**149**	**328**
Average open time per door opening (seconds)	**7.5**	**7.4**
Total number of door openings	**142**	**594**
Average number of door openings per day	**16**	**33**

Note: the total number of door openings shown above is not obtained from this data but from a separate count of the number of times the refrigerator was opened and closed, as several behaviours might have occurred in series with only a single door opening.

Table 9 - Times and Frequencies of Behaviours

There are also increases in the amount of time spent just looking into the refrigerator and considerable increases in the general all round activity with the refrigerator in Study B. Clearly these observations cover only a small sample size, but the results are in line with other refrigerator studies. ELIMA [2005] showed a typical range of opening times for refrigerator doors of between 8 - 19 seconds and two surveys, one in France of 143 households [Laguerre et al. 2002] and another in Malaysia of 104 households [Saidur et al. 2008], revealed 81% and 78% of households opened their refrigerators between 11 and 40 times a day respectively.

One thing to note would be the increased average time taken to take something compared to putting something in. This suggests an element of looking and searching time is included in this behaviour. Figure 25 demonstrates a large variation in the time taken to perform these simple actions with the most common time being three seconds for both: one second to open the door, one second to get or load an item and one second to close the door.

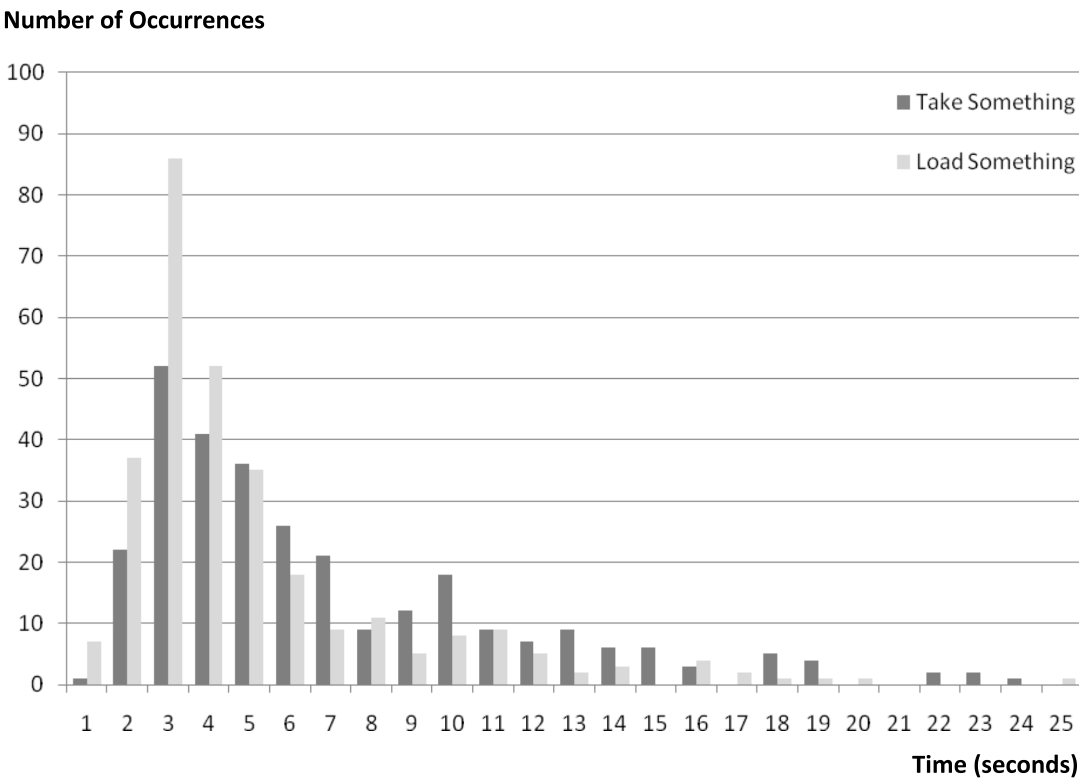


Figure 25 - Variation in times recorded to either take something or load something into the refrigerator (data taken from Study B)

Figure 25 clearly shows the three-second time as the most common time for both these actions, with 86 occurrences for loading something and 52 for taking something. One explanation for the considerable range in the times taken for "taking something" is that this incorporates an amount of searching and finding time. This searching time is not required when returning the item as its location and destination are already known.

Variations in the data between the two studies can be easily explained by the lifestyles of the people under observation. The users in Study A tended to be away from home during the day and when cooking made simple meals with relatively few ingredients. Conversely in Study B, although they had a similar working pattern to those in Study A, performed much more elaborate meal preparations. But which of these individual behaviours has the greatest energy impact? The next section takes this time and frequency data and combines it with the energy impact data from Research Appendix 9.2.7 to give designers the information they require to make informed decisions about how to design energy using products such as this.

A unique feature of these video studies is that not only can the behaviour be identified and how it is being carried out, but it is also possible to see what foodstuffs and drinks are being used. The use of an adequate camera and a suitable viewing angle enables identification of the items being removed and replaced. Table 10 highlights the five most commonly witnessed items being removed or replaced in the refrigerator; milk is dominant in both studies as the most accessed item. This is then followed by other drinks; orange juice in study A and a collection of items such as orange and apple juice, wines and beers all under the umbrella term of "drinks" in study B. The third most removed or replaced item was butter or margarine. This data is supported by observations into refrigerator behaviour by a researcher at Loughborough who in a 24 hour study identified that milk and then margarine were the most frequently accessed items. 40% of door openings were for milk and 10% for margarine [Tang et al. 2009].

Table 10 also shows the large number of items that had to be discarded from the top five because it was not possible to clearly identify what they were. For Study B this is a large number of items and so there is an inaccuracy in this data. However the information for milk and drinks, from both studies, is exact because the nature of where they are stored in the refrigerator door makes them clearly visible.

Study A	Frequency	Time (seconds)
Milk	40	205
Orange Juice	15	85
Butter	11	46
Cheese	11	53
Egg	9	55
Misc / Unknown	46	316

		Time (seconds)
Milk	165	741
Drinks	49	238
Butter	30	117
Meat	9	84
Vegetables	6	79
Misc / Unknown	340	2756

Table 10 - Times and Frequencies of the five most commonly used items

This knowledge could be helpful when designing a new User-Efficient refrigerator as items that are used frequently might benefit from a specific location within the refrigerator, separate fast access, or some other design feature or separate product just for them. The ability to uncover more detail than just what is being done adds depth and richness to this observation research. However, due to the camera positions in these studies this researcher was not able to obtain specific data such as this with any certainty.

It is important to note at this stage that this coding process required a considerable amount of time to perform accurately. In order for this to be adopted in industry it might require a more automated approach, using perhaps sensor information on both the refrigerator and its contents to establish the action and motive for each occasion of use.

5.3 Quantifying the Energy Impact of Behaviour

Table 9 showed a list of 12 different observed behaviours based on the data set from the two kitchens. Designing a product that meets all of these different requirements is a difficult task and many of these behaviours might be insignificant in terms of energy impact. High impact in terms of refrigerator use refers to the length of time the refrigerator door is open: the longer the door is open, the more cold air escapes and the higher the energy use of the product. This list can therefore be reduced to only a handful of high impact and significant behaviours. The top five highest energy impacts, based on total time open and taken as a combination of Study A and Study B, are shown below in table 11. Also shown is a rounded percentage of the division of total open time for each of these behaviours from the studies.

		Study A	B
1.	"Open door to take something"	35%	40%
2.	"Open door to load something" (and "load shopping")	24%	32%
3.	"Open door to look / search / sort inside"	22%	17%
4.	"Leave door open to do something with the removed item"	13%	4%
5.	"Leave door open to do something not related to the refrigerator or item"	6%	3%
All other observed behaviours combined		>0.5%	4%

Table 11 - Top five Highest Energy Impact Behaviours

Table 11 shows the percentage energy impacts of each of the five behaviours; the three behaviours with the largest impact in both studies are: taking items, loading items and searching for them. The remaining two relate to behaviours where the door is left open and the person walks away, perhaps to do something with the item they removed or not. In either case the person is not benefiting from the door being open. The values have all been rounded for simplicity and ease of comparison.

Using the average figure of 0.68 Wh / second open [from Mennink et al. 1998, Saidur et al. 2002, Research Appendix 9.2.7] the top five behaviours from table 11 can be quantified with an energy value associated for each. First, the amount of "wasted" time for each behaviour must be established. The time associated with behaviour one "Open door to take something" and behaviour two "Open door to load something" (and "load shopping") could be reduced to the three-second target ideal open time that was established in figure 25 as the most common time for both of these.

The total user-related energy used (table 12) is the total amount of energy used by all the observed behaviours, whereas the energy values in the main body of the table only include the wasted energy and therefore have had the three second action removed from behaviours one and two. Behaviour three "Opening the door to look / search / sort inside" can be classed as entirely wasted time and energy and so is included in full in table 12. The final two behaviours (four and five), "leave the door open", can also be included in their entirety as having the refrigerator door open in these two instances provides no benefit to the user.

Behaviour	Study A	Study B
Total User-Related Energy Used (per year)	**36.9 kWh**	**81.3 kWh**
1 Open door to take something	180.88 Wh	992.12 Wh
2 Open door to load something (and load shopping)	66.64 Wh	516.12 Wh
3 Open door to look / search / sort inside	204.68 Wh	675.24 Wh
4 Leave door open to do something with the removed item	114.92 Wh	146.20 Wh
5 Leave door open to do something not related to the refrigerator or item	55.08 Wh	127.16 Wh
Total User-Related Energy Losses During Study	**0.62 kWh**	**2.46 kWh**
Total User-Related Energy Losses (per Year)	**25.23 kWh**	**49.82 kWh**

Table 12 - Energy considered wasted for studies A and B

The results from table 12 show how a young family, with a single child, increased the stated energy use of a refrigerator by 49.82 kWh a year, an increase of 20% on the average energy use of a standard sized refrigerator, taken to be approximately 250 kWh for a unit of this size. With this quantified data to hand, a design team could now use this information to guide their design efforts. The following chapters explore in detail how this could be achieved.

Research Questions (RQ)		Research Activity	Chapter

Objective 1: To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour

RQ 1.1	What is poor energy-using behaviour?	Literature Review	2.0
RQ 1.2	How can it be changed?		
RQ 1.3	Can behaviour change be designed?		

Answered

Objective 2: To create a way of measuring the energy impact of user's behaviour

RQ 2.1	What are suitable metrics?	Energy Modelling	4.0
RQ 2.2	How significant is poor energy-using behaviour?	Use Scenarios	
RQ 2.3	How can information on behaviour be collected and turned into useful data?	Observational Studies	5.0

Answered

Objective 3: To explore how designers might use information on behaviour to design

RQ 3.1	How can this information be used to aid the design of products?	Literature Review	6.0
RQ 3.2	How do designers interact with this information?	Design Experiment	
RQ 3.3	How should this information be presented?		
RQ 3.4	What impact will it have on the design output?		

Objective 4: To investigate if it is possible to design products so that they can only be used in an energy-efficient manner

RQ 4.1	What would such a design process look like?	Participatory Research Design Process Demonstrator Industrial Consultation	7.0
RQ 4.2	Can a product improve the impact of poor energy-using behaviour?	Product Demonstrator	

Research Progression and Chapter Outline

6.0 Using Information in the Design Process

Engineering designers often work in small groups or teams to generate and evaluate ideas in the early stages of a design process and is most commonly seen when tackling complex problems [Stempfle et al. 2002]. These early concepts typically then progress to some form of design stage gate or feasibility study where they are explored and developed further. The decisions made during the early phases of a design project can often have exaggerated effects further down the development process [Asiedu et al. 1998]. Thus improving the effectiveness of early design-phase decisions could prevent exaggerated negative or even produce beneficial consequences. However, due to industrial constraints, designers are often placed in situations that require them to generate ideas and concepts quickly. Obviously this might compromise the quality of these ideas [Briggs et al. 2007, Howard et al. 2010a].

A knowledge gap was identified after collecting data on the energy impacts of inefficient behaviour. This gap related to the use of this information by a design team, as in general design research the role that information plays in enhancing or even inhibiting creative design activities is an under researched area [Howard 2006] and there is little empirical research in this field. In addition to the use of this behaviour information, as collected in chapter 5.0, being used purely as a design check to ensure that the proposed new design saved more energy than it cost to implement. The question was asked: how could this behaviour information be presented and used by a design team in the most effective way? The aim of this chapter is thus to identify factors that might allow designers to produce ideas of a higher quality in a limited timeframe by using this behaviour information; in other words, to perform more creatively.

Information to aid creativity can come in many different forms and formats, from ethnographic video of a user encountering a problem, to a photograph or written description or numerical data. Irrespective of information's format, its purpose can either be as a divergent creative stimulus, encouraging designers to think more widely around a problem, or as a convergent stimulus focusing designers' thoughts on a more important issue.

6.1 Creative Stimuli

A considerable amount of research has been carried out into what makes creative people deliver creative solutions, from the effects of incubation periods, where the subconscious mind is given time to 'think' over a problem, through to the use of "loafing about" and "humour" [Aksnes 2006]. In general, research has shown that the process of generating ideas is enhanced by providing three main elements: nurture [Mauzy et al. 2003], freedom and time [Stemberg et al. 1993, Frey 1999]. These three factors often come under pressure by industrial constraints, additional tools or aids have been sought to help designers. One of the most commonly researched and discussed is that of using creative stimuli.

It has been demonstrated empirically that exposure to visual stimuli at the conceptual design phase, with or without instructions to make use of such stimuli, has a positive effect on idea generation [Goldschmidt 2009]. Consequently creative stimuli are increasingly used. In general, creativity tools or methods have propagated throughout industrial design practice as a way of improving idea quantity and quality in limited time frames, with the preferred creativity tool being the traditional brainstorm [Chakrabarti 2003].

It has been said that creative ideas are new and unexpected combinations of existing knowledge 'items' in memory and new information 'superimposed' on them [Goldschmidt 2009]. Anecdotal evidence suggests that designers store, physically or in their memory, visual images and artefacts that they consider might be potentially helpful as sources for future design ideas. Goldschmidt neatly demonstrates this phenomenon of collecting potential stimuli with a quoted description of Le Corbusier's design process:

> *"His mind was well stocked with ideas, devices, configurations and images gleaned from tradition, from painting, from observation, and of course his own earlier works... at the right moment images would flow to the surface where they would be caught, condensed and exteriorized as sketches."*

This mental store of ideas, the person's culture, life experiences and his or her ability to access or recall this information in a creative sense, all contribute to a person's ability to be creative. Goldschmidt's mental store of ideas could be, for any particular problem or design activity, visualised simply as an area known as the "idea space". This metaphorical space encompasses every possible idea for that design activity [Elias et al. 2011a]. The individual's share of this idea space within it would be of different sizes depending on the person; a creative person would have a larger space than a non-creative person, because they have a larger mental store of ideas. In visual terms (figure 26) the use of creative stimuli can enlarge the individual's idea space stimulating their thoughts and mental store to generate new designs and solutions.

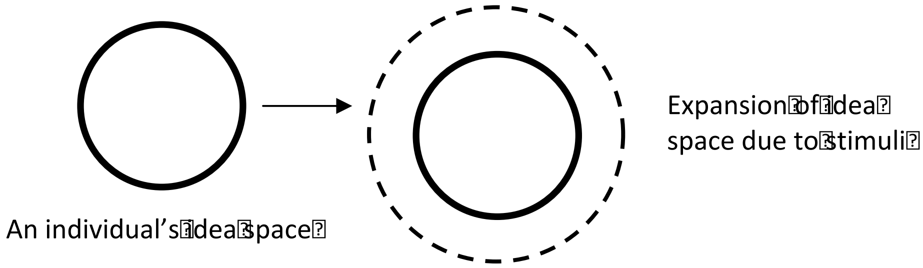


Figure 26 - A visual representation of the idea space and the advantage of using stimuli [Elias et al. 2011a]

A current leading design consultancy (IDEO) have embraced this idea and over many years built up an extensive collection of different materials, mechanisms, toys and gadgets that they have formed into a single reference library and inspiration source (figure 27). The collection of creative stimuli has in fact become so large that a member of staff is now employed full time just to maintain and record it, making it accessible for all employees to use.

Despite considerable research into the creative process, there has been limited exploration of what format stimuli should take; the assumption has been that visual stimuli, whether video, images or physical artefacts, are best since designers tend to work in a visual environment. This however does not have to be the case, written texts and descriptions can also be effective methods of inspiration, communicating ideas that might be impossible to express through visual images and reducing potential stimuli drawbacks such as 'fixation' [Goldschmidt 2009]. As part of the process of rooting through and searching for new stimuli, either physically or mentally, designers can often become attached to ideas, which they develop further at the expense of searching for better ones [Cardoso 2009]. This attachment to an idea is known as "fixation" and can greatly reduce the effectiveness of idea generation and the designer's creative performance.

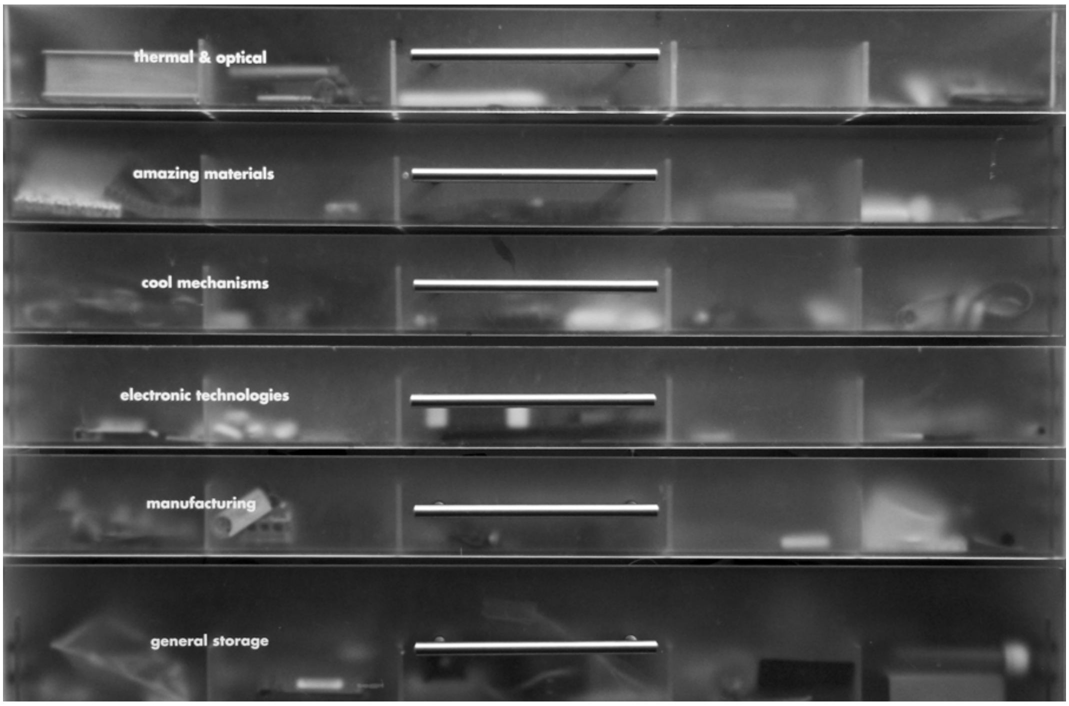


Figure 27 - A section of the IDEO inspiration collection from their Palo Alto Office in 2009.

Consequently, a number of research questions arise on this subject of using behaviour information to improve the user-centred design process. They relate to four main topics:

- Timing — When should behaviour information be introduced to a design team if it is to encourage design creativity?
- Relevance — Does the behaviour information need to be relevant to the design task? Or could irrelevant user information be useful?
- Format — In what format should the behaviour information be delivered to a design team? Should information be video, data tables or both?
- Granularity — How detailed should the behaviour information be? Is an overview of the problem sufficient or would specific data be beneficial?

These are obviously questions of relevance to all design research. In this research, these variables are tested in the context of user-centred design to reduce the environmental impact of products. The user behaviour data collected in section 5.2 represents the potential stimuli material for the design process. Therefore an experiment was devised that would test these variables in laboratory conditions and begin to form answers to these questions.

6.2 Design Experiment

The experiment set out to explore and test the hypothesis that a design team will benefit from having user behaviour information to hand that is relevant to their task during the early design phases of designing a new user-centred eco-design product, in this case a new domestic refrigerator. Having collected user behaviour data the overall aim was to establish in what format this data could best be used, in order to generate the most beneficial results for the design of energy efficient products.

The key metrics for creativity, based on what is commonly used in other design research studies [Nijstad et al. 2002, Perttula et al. 2007, Howard et al. 2010b], are an improvement in the number, originality and effectiveness of the ideas produced. Effectiveness here includes measures of relevance, appropriateness and quality. In order to determine this measure of creativity change, small teams of designers were given a design brief and information in a variety of formats. As can be seen in later sections in this chapter, their design output was then compared that of two control teams. In addition to this quantitative assessment, other possible benefits or drawbacks were assessed in a qualitative discussion of the teams' performances.

The work of this experiment was led by the author and, with the assistance of other researchers, is being turned into three journal papers [Elias et al. 2011b, Cash et al. 2011a and Cash et al. 2011b] which give detailed accounts of the experimental method, results and use of a placebo control group. Some of the following sections are supported by additional analysis, material and results in the Research Appendix and will be highlighted as and when they are relevant, but are not required as compulsory reading.

6.2.1 Participant Selection and Experiment Setup

The experiment involved five teams, with three participants in each, who were all given the same initial information: some background information on designing products to reduce the energy impact of poor use; a description of what roles they are to take; and a design brief asking them to design a new domestic refrigerator, focusing on reducing the impact of inefficient use.

In addition, extra information was provided to four of the five teams to act as a creative stimulus and test the experimental hypothesis. For three of these information sets, details of inefficient user behaviour was provided, based on the data from chapter 5.0, focusing the team on the brief. The fourth was a placebo intervention that gave task-neutral information.

As far as possible, all factors relating to participant expectation, pre-conditioning and the information delivery were controlled as this has been shown to effect results [Liikanen et al. 2008, Purcell et al. 1996]. The aim being that the only controllable difference between the teams was the presence and content of additional information provided to them. Table 13 shows the five experimental conditions:

Team	Title	Treatment	Description
Team 1	"Control"	No treatment control	No additional information provided.
Team 2	"Placebo"	Placebo treatment control	A 15 minute task-neutral video of two people discussing their kitchens, the appliances they had and general appearance.
Team 3	"Video"	15 minute active video treatment	A 15 minute ethnographic style film, including discussion and details of how and how often the refrigerator is used.
Team 4	"Data"	Data treatment	A printed list of the occurrence of different behaviours and their energy impacts including data on which products were most commonly taken out of or put into the refrigerator.
Team 5	"Data + Clips"	Data and video clips treatment	Same data as team 4 and a series of eight short, silent, hidden-camera video clips demonstrating each of the behaviours, totalling approximately 13 minutes of footage.

Table 13 - Team Classification and Information Inputs

The 15-minute placebo video involved two people discussing their kitchens, the appliances they had and general appearance of their kitchens. The length and style of the video was similar to that of the active video but included no specific information of use to the team. In this way it was hoped that the placebo team would experience the effects of receiving an information intervention but without obtaining any useful information from it, thus acting as a second control group for this experiment. The use of teams was preferable to individual designers because it is possible to balance the performance of a strong individual amongst other members, reducing the likelihood of results being distorted by single outstanding participants working alone.

Team Size

Opinion on optimal team size varies, with some studies showing that larger teams produce more ideas [Hare 1952] while others oppose this [Hwang et al. 1994, Hackman et al. 1970]. Larger teams also take longer to reach a decision and require clear leadership to be consistently effective as member dissatisfaction increases and participation decreases with size [Cummings et al. 1974, Hackman et al. 1970]. In practical experimental terms though, as a team gets larger, keeping track of the discussions and performance becomes harder. A larger team gives rise to the possibility of parallel discussions and makes recording them increasingly complex and prone to error. A smaller team of two people or even a single designer not only suffers the effect of having single over-performing or under-performing participants, but working in a pair or alone increases the amount of silent 'thinking' time where a video or sound recording cannot capture the cognitive activities of the participants.

Overcoming this relies on the 'thinking aloud' protocol of concurrent verbalisation where a participant is asked to give a continuous narration of their thoughts. There are however some significant disadvantages to these 'thinking aloud' techniques, such as the actual act of verbalisation changing the behaviour and performance of the speaker. Alternatively the speaker might give incomplete or irrelevant accounts of their thoughts, reporting a parallel but independent thought to those that are actually being employed in the task [Cross et al. 1996]. One additional consideration was the practical limitation of finding suitable participants. The term suitable was used to define a group of people who were uniform in backgrounds and experience, with some knowledge of design and creativity processes. As a result participants were selected from postgraduate students and staff at the Department of Mechanical Engineering, University of Bath. They had all received academic training and had experience in creative engineering design, brainstorming and general creativity processes. The choice of using postgraduate engineering students, research officers and teaching staff was made because it was thought they experienced the highest commonality and uniformity between participants. They were also sufficiently experienced enough in creativity methods to simulate a professional design practice. Selecting participants from a body of undergraduate students would open up the experiment to too large a possibility of variation in background knowledge, experience and ability, undermining any results. Whereas, the use of professional designers was not thought to be realistic for practical limitations of the experimental set up.

Using larger team sizes would require more participants and it would have been hard to find people with a similar background and knowledge to those already chosen. This commonality of the participants is an important element of balancing the teams and experimental rigour might have suffered if this was broadened. In summary, table 14 shows the various attributes of team size. A team size of three was chosen by this researcher for all five teams for the reasons already explain.

Team Size	**Participants Needed**	**Recording Method**	**Drawbacks / Benefits**
1	5	Concurrent Verbalisation	A single strong / weak participant may affect results. Concurrent verbalisation is difficult to give replicable information on thought process [Cross et al. 1996].
2	10	Listen to Discussion	A single strong / weak participant may affect results, but two people removes the need for enforcing verbalisation as their discussion can be recorded easily.
3	15	Listen to Discussion	Strong / weak participants are partially balanced amongst other team members. Participant discussion is easy to follow. No parallel discussions possible.
4	20	Listen to Multiple Discussions	Strong / weak participants are balanced. Greater idea generation potential. Multiple parallel discussions may be hard to follow. Large number of participants required.
5	25	Listen to Multiple Discussions	The same drawbacks and benefits as having four people per team but literature also suggests they would require formal team leadership to be effective [Cummings et al. 1974, Hackman et al. 1970].

Table 14 - Team size drawbacks and benefits matrix, with chosen size of three highlighted

In order to further reduce participant and team-related variables, such as levels of team creativity, work rate or a team's ability to work well as a team, an element of team balancing was required in addition to the commonality of participant backgrounds. Team balancing was therefore based on the results of a Belbin Team Role test, table 15.

Team Balancing

Belbin Team Roles are one of the most commonly used assessment frameworks for measuring people's character [Senior 1997] and is used commonly in interview situations. It was chosen over the other most popular framework, the Myers-Briggs Type Indicator, because its character classifications were more obviously connected with the experimental task. Belbin described eight possible Team Roles [Henry 1999] but this was later expanded to nine, with the definition of a Team Role being "a tendency to behave, contribute and interrelate with others in a particular way" assessed using a series of questions [Belbin Website].

Team	Person	Coordinator	Shaper	Innovator	Evaluator	Implementer	Team Player	Networker	Finisher	Specialist
1	Person A	7	8	11	3	11	4	24	0	2
	Person B	9	28	8	2	15	2	5	0	1
	Person C	5	13	6	8	13	6	0	17	2
2	Person D	5	9	12	8	13	6	5	0	12
	Person E	2	15	7	9	13	3	9	7	5
	Person F	4	5	1	6	12	11	4	11	14
3	Person G	13	10	15	2	6	6	13	5	0
	Person H	9	2	2	7	9	11	8	3	19
	Person I	1	6	7	8	12	10	4	14	8
4	Person J	6	7	14	4	10	5	16	1	7
	Person K	0	0	6	17	19	14	0	3	11
	Person L	1	14	4	13	5	6	0	17	10
5	Person M	5	12	12	4	4	6	20	4	3
	Person N	0	3	7	18	8	8	4	13	9
	Person O	4	12	8	11	6	6	2	11	10

Table 15 - Belbin Team Roles results for the five teams

Most of the participants in table 15 showed a spread of points amongst several Roles, which is common in these tests [Belbin Website]. This researcher considered the "innovator" and "shaper" roles as being the most significant of roles for the design task to be undertaken and thus team balancing on the basis of these roles was an important consideration. The "innovator" role is creative, an 'ideas person' and problem-solver. The "shaper" is dominant, a task-focused leader, who will shape others into achieving the aims of the team. As a result teams were allocated a strong "innovator", with a score above 10 points and, secondary to that condition, each team would have a strong "shaper". All other scores were balanced as much as possible given pragmatic considerations such as participant availability. In addition, where possible close friends or working colleagues and participants with shared working experiences were separated.

6.2.2 Experiment Procedure

The experimental period, of just over two hours, was divided into four phases (figure 28). Two phases focusing on divergent idea generation followed by two on convergent idea selection [Rietzschel et al. 2006]. Each phase had a different activity focus and was repeated in turn for each of the five teams. It should be noted that most creativity studies last between 20 – 60 minutes in total [Liikkanen et al., 2009, Collado-Ruiz et al. 2010] but due to the multiple phases of this experiment, including idea assessment and development as well as the initial 60 minutes of design time an extended period of time of two hours was thought beneficial.

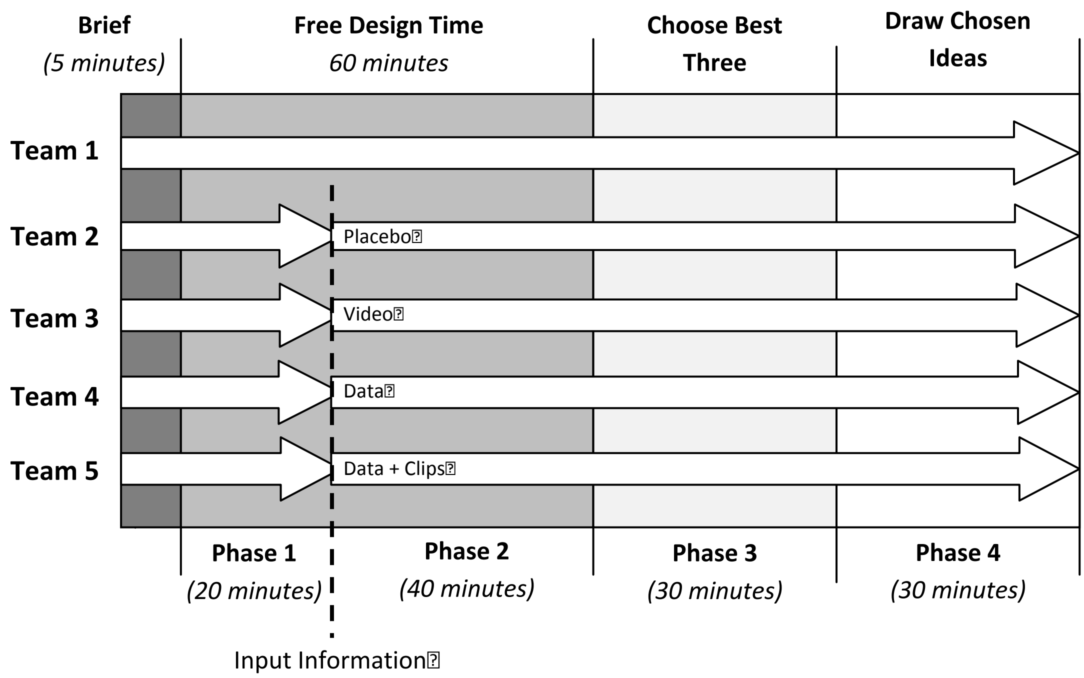


Figure 28 - Experimental Timeline

Phases one and two were classed as "free design time" in which the teams could complete the first task of generating ideas. There were no prescribed design methods during these phases. Phase three gave the teams additional time to generate and develop ideas, but also demanded the selection of the best three final concepts. Phase four gave the teams time to draw and explain the final concepts.

Brief During a five minute introduction the experiment controller read instructions from a pre-prepared script, attention was paid to briefing the teams uniformly, in order to avoid the effects of cueing [Liikanen et al. 2008, Purcell et al. 1996]. Participants then had time to read the briefing material, which asked them to design new domestic refrigerator concepts and paper and pens were then issued and the experiment began.

Phase 1 This was the same for all five teams, consisting of 20 minutes of uninterrupted design time at the start of which the teams were instructed that they had 60 minutes to develop as many ideas as possible. The aim of this phase was to allow a fair comparison between all five teams and a before-and-after comparison before any information was provided, acting as an additional control element to the experiment.

Phase 2 As soon as phase one ended four of the teams received the additional information (table 13) and continued with idea generation.

Phase 3 This phase was introduced by the experiment controller and consisted of 30 minutes for teams to develop their three most effective and feasible refrigerator concepts, based on criteria provided to them.

Phase 4 In the final phase of the experiment, the experiment controller asked the teams to draw and annotate their chosen three refrigerator concepts onto single sheets of A3 paper, one concept per sheet, with the specific instructions that it must be understood from this piece of paper alone. The aim of this was to make analysis and comparison of the final refrigerator concepts faster and simpler without the need of a lengthy review of the video footage in order to understand them.

The phases of this experiment were designed in such a way that each phase would represent a different aspect of the design process, idea creation, idea assessment and idea development:

- Phase 1 was designed to allow a comparison to be made between all five teams since at this point all the teams were equal in their knowledge and no additional information had yet been introduced, in this way it could be used as an additional level of experimental control;

- Phase 2 would then investigate the impact the introduced information has on the creativity of the teams as a comparison with before the information introduction and between the teams;

- Phase 3 would reveal insights into how this behaviour information could be used as part of the assessment and selection process;

- Phase 4 would compare the team's final ideas and look for originality or uniqueness.

The whole experiment was recorded on film from several angles. Figure 29 shows a screenshot of the video feed from one of the experiments. Channel 1 (CH1) shows a view of the team from above, Channel 2 (CH2) shows a view from the side, Channel 3 (CH3) shows the feed from the laptop screen if it was used and Channel 4 (CH4) was blank.

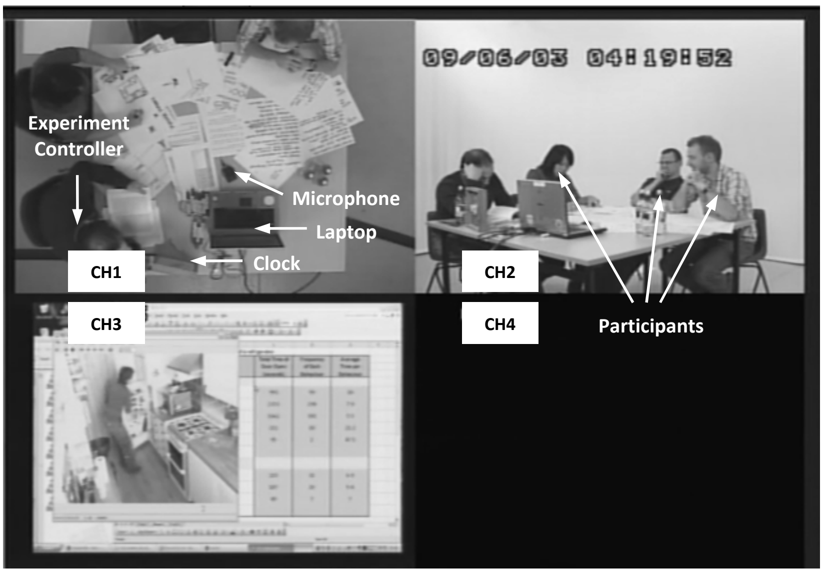


Figure 29 - An example screenshot of the experimental video feed in action

6.2.3 Results

Since none of the designers had any previous knowledge of the experiment task, the only controllable major difference between the teams was the additional information provided. A combination of qualitative and quantitative analysis of the experiment was performed, using the three previously noted metrics for creative output:

1. **Number of ideas**

Counting the number of ideas a team creates is a relatively simple measure to obtain and can provide a quick insight into how creative the team was. An idea, in this context, is defined as any written, drawn or spoken thing that could be used as a design or design aspect. Each new idea was recorded when first discussed, based on the video recordings. During the sessions many ideas were stated at an early stage and then repeated later or revisited in greater detail; these were counted as a single idea for the purposes of this study.

In order to achieve this accurately, every idea was noted, with a quotation of what was said at the time. The idea was then simplified into common terms and shortened descriptions. These were then compared to the other ideas produced in order to check for any duplication or double counting of the same idea. Table 16 shows an example section of the finished review process for Team two. The table shows the time the new idea was first discussed, what was said and a shortened description.

Time	Quote	Description
00:02:55	"Super obvious milk goes here"	Milk Section
00:05:35	"Buzzer"	Door Open Alarm
00:07:11	"Maybe have a less deep refrigerator"	Shallow Refrigerator
00:08:29	"If every time you put something in, it had a place to go"	Food Locations
00:08:36	"Sliding dial with the date you put it in"	Food In Date Dial
00:09:51	"Child lock"	Child Lock
00:11:39	"They could record their child's voice saying close me"	Recordable Door Alarm
00:12:05	"Speakers in it too"	Inbuilt Speakers
00:13:59	"A chamber that is used often, for products that you're using all the time and keeping stuff that you are using once a day"	Frequent Use Section

Table 16 - Example ideas from the idea review of team two

The idea-count should also include ideas that were dismissed by the teams as they were saying them, for example:

Person D *00:55:37* *"I don't think we can actually get people to throw things out, we can't have an [ejection of old stuff], you've got to give people some credit for brain power!"*

These idea-counts can be arranged into an idea timeline (figure 30), also known as "Ideation Fluency" [Weir et al. 2005]. It also demonstrates how a team's idea-generating performance changes during the course of the experiment. Idea timelines for all five teams can be viewed in Research Appendix 9.3.2. An interesting observation from these time lines is that this design period of two hours is unusual for a design experiment, with most studies lasting between 20 – 60 minutes in total, because they cite a strong decline in idea generation after the first 40 minutes, with many studies stopping before this [Liikkanen et al., 2009, Collado-Ruiz et al. 2010]. Figure 30 also shows a decline after 40 minutes but then shows a resurgence of ideas and a second peak of creativity.

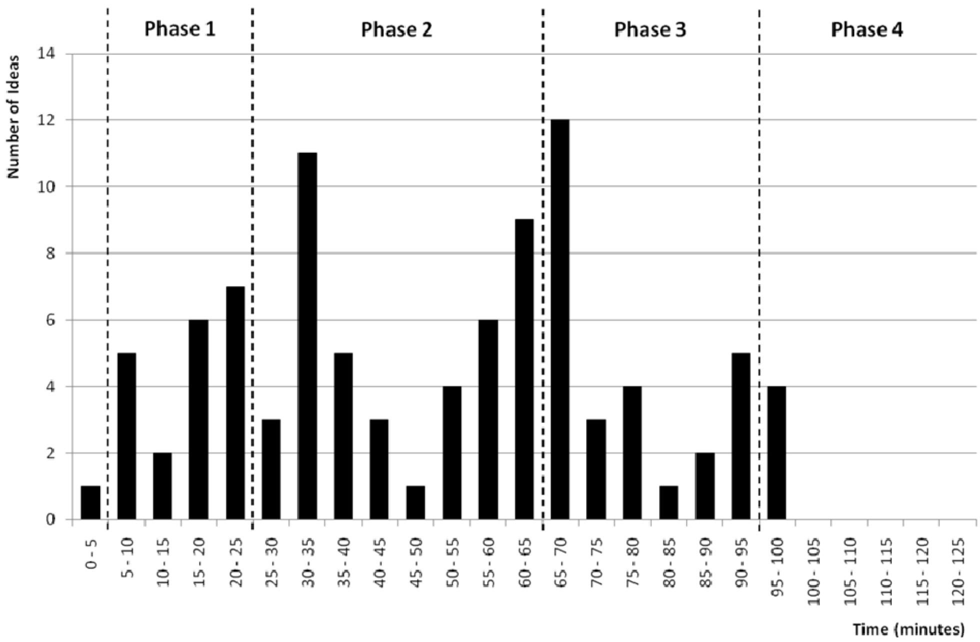


Figure 30 - The number of ideas produced every five minutes for team one

The total count of ideas shows clearly that team one, the control team with no additional information, produced over twice the number of ideas as some of the other teams (table 17). This is in contrast to the expected result of information being a design stimulus and, studying all the team's timelines from Research Appendix 9.3.2, suggests that the information could have acted as an interruption, reducing the number of ideas being produced.

	Total Number of Ideas Produced
Team 1 - 'Control'	94
Team 2 - 'Placebo'	47
Team 3 - 'Video'	40
Team 4 - 'Data'	39
Team 5 - 'Data + Clips'	57

Table 17 - Total Idea count for all five teams

This does not seem an unreasonable conclusion since in a time-pressured situation such as this, a naturally creative team with no interruptions would expect to do well. Teams two and three both had a 15 minute interruption as they watched the supplied videos. It is interesting to note that during these videos, neither teams discussed ideas as the video played, instead choosing to watch and listen in silence, effectively reducing the total time they had available.

2. Originality of ideas

An assessment of the originality of the ideas was made by comparing all the teams' final three chosen concepts with each other. An image and description of each of the team's final concepts can be viewed in Research Appendix 9.3.3. The logic of this comparison was that if the concepts are all similar in nature, a judgement can be made that the originality or novelty of these ideas is not high. Based on this hypothesis, a comparison of the final concepts was undertaken and there was no obviously dominant team, with many similar, if not identical, ideas being shared amongst them.

It is this similarity of concepts between the teams that must logically lead to an initial negative finding for the hypothesis. Based on these results, providing additional information does not appear to improve the creative originality of the design teams' outputs as hypothesised.

However, this may be partly due to a number of experimental factors including the participants' familiarity with domestic refrigerators and their use. Thus the additional information did not significantly contribute to the existing knowledge base of the participants, limiting its effect and impact on them. This is supported by anecdotal evidence from professional design agencies who state that for problems such as this they would only investigate users who are unusual, have a particular difficulty with a product or live a certain lifestyle that would generate some novel or interesting ideas.

3. Effectiveness of ideas

Lastly the effectiveness of the teams' ideas, a group term for 'Ideation Feasibility and Variety' [Weir et al. 2005], was examined to discover if a team of limited creative quantity had instead produced higher idea quality. To determine an idea's effectiveness and relevance, the researcher examined all the ideas, randomised to mitigate any team bias and made a judgement based on the following criteria:

- The idea reduces the impact of inefficient use by addressing a number of key engineering requirements, such as reducing opening time and preventing air flow, as two examples;

- The idea reduces the impact of inefficient use but also adheres to a number of core psychological and behavioural requirements, such as not relying on the user performing an action that is more inconvenient or time-consuming than the original inefficient behaviour;

- Ideas must be feasible with existing technology and must also not be so expensive as to inhibit implementation.

The use of subjective expert judgements, such as this, is an established and common method for measuring aspects of creativity in design experiments [Baer et al. 2004, Silvia et al. 2009]. In spite of this, as an additional level of rigour, an intra-reliability check was also made, by the same researcher, on a second occasion to ensure repeatability of the results.

Once these checks were completed the effective ideas were then re-grouped into their respective teams and ideas that were merely variations on a theme were removed in order to avoid double counting of the same idea thus preventing exaggeration of a team's performance. For example there are many ways a self-closing door could be made. However, the idea's function is still the same and as such will be treated as a single idea.

Table 18 shows the results of this reorganisation under headings of relevance to the brief and effectiveness in dealing with it. This sheds a new light on the data suggesting that although information stimuli might interrupt and cause fixation, a smaller percentage of the ideas produced are irrelevant and a greater percentage are effective, thus supporting the hypothesis.

Firstly teams one and two with no or neutral information performed at a similar lower level. Secondly, teams three, four and five consistently produced proportionally 20% more effective ideas than the two control teams. Thirdly, the level of irrelevant ideas is significantly higher for the teams without additional relevant information. These conclusions all support the hypothesis that relevant additional information aids the design process.

	Total Number of Ideas Produced	**Number (and Percentage) of Irrelevant Ideas**		**Number (and Percentage) of Effective Ideas**	
Team 1 'Control'	94	22	(23%)	30	(32%)
Team 2 'Placebo'	47	10	(21%)	16	(34%)
Team 3 'Video'	40	5	(13%)	22	(55%)
Team 4 'Data'	39	2	(5%)	22	(56%)
Team 5 'Data + Clips'	57	3	(5%)	30	(53%)

Table 18 - Idea relevance and effectiveness comparison for all five teams

A qualitative discussion and assessment of the design activities and performance for each team was also carried out and is available to view in detail in Research Appendix 9.3.4. This examined how they approached the problem, how they interacted with and used the provided information and how they selected their best ideas. Coupled with the quantitative results shown previously, this provides some interesting insights to how user-behaviour information should be introduced to a design team and the format it should take.

6.2.4 Design Insights

By undertaking this experiment, many useful insights have been gained on how design teams operate and process information, relating to the timing of the information stimuli's introduction, its relevance, format and granularity:

Timing *The time at which information is introduced must not interrupt the team's working pattern but be a natural progression of their thinking.*

It was evident from the five experimental sessions that introducing information at a fixed point in time was not optimal for stimulating ideation in the teams and would have been more effective if it were introduced once the rate of ideas had declined, as was the case with design research from Howard et al. [2010c], or when the team's ideas had become less relevant to the brief. This finding questions the generally accepted wisdom that information is always a design stimulus and could form a significant area for further study, namely, when should additional information be introduced and how should the best time be identified.

Relevance *The information must be relevant and useful to the task at hand.*

This is a self-evident statement based on the findings in table 18, where the teams with relevant information all produced a greater percentage of relevant and effective ideas. This is also supported by the performance of the placebo group, where the neutral information had no beneficial impact on idea relevance or effectiveness when compared to the team with no information.

Format *The way the information is presented is suitable to the audience and situation in which it is being used.*

Consider teams two and three, who were shown a full length video intervention with sound. They sat in silence whilst watching and listening to the videos, making occasional notes and then did not return to play all or part of the video again. The videos were also infrequently brought up again in conversation. The teams with data on the other hand frequently returned to the information, discussing it at length and referring to it when justifying or criticising ideas. Team five also had video, in addition to the data, but each clip showed a series of different cases of a particular behaviour being performed and were short and silent. The format of these silent clips promoted discussion since the lack of sound encouraged participants to speak as they would not be talking over a potentially important point.

Granularity *The information is at a sufficient level of detail.*

A qualitative assessment of the sessions suggests that the level of detail in the data for teams four and five was perhaps more than necessary at this stage in the design process. This high level of detail in the data actually slowed their progress and reduced their available time to generate ideas. This complexity of data led to the teams needing to clarify and discuss unnecessary specifics. Thus causing confusion, distracting them from the task and ultimately wasting time. A more useful presentation would be a ranked list of which behaviours were worth considering for design and which were not. This would provide the team with a design focus rather than points that needed more discussion. This insight is supported by a similar finding from Collado-Ruiz et al. [2010] who found that low levels of detail in information was a positive aide to creativity. The raw data could then be reintroduced later as a check for the feasibility of the concept to see whether the new design concept will not use more energy than the savings delivered.

6.2.5 Experiment Conclusions

The focus of the experiment was to explore the connection between providing information in different forms and seeing which, if any, had a greater beneficial impact on teams' idea-generating performances. 'Beneficial' was defined by an increased number, greater originality and greater effectiveness of the ideas produced by the teams with additional information, compared to the control teams. Overall, the experiment yielded some interesting and varied results, which ultimately both support and refute the hypothesis.

Two negative findings were identified: First, regarding the number of ideas produced, the control group performed considerably better than all other teams (table 17). This can be explained by the additional information provided acting as an interruption, which disturbed the team's creative process and removing available design time. This interruption effect is seen in all four teams that received information and is supported by the presence of the placebo team. Without the placebo team this decline in design output could be attributed to the time required for the teams to cognitively process, discuss and use the information in their designs. Conversely the placebo team's video, due to its irrelevance to the task, highlighted the interruption effect as the likely cause. The second negative finding was that all the teams produced ideas which were equally creative, sharing many common features. This suggests that where the subject is known to the designers, providing additional information will not improve the creativity of the design team. This is of great interest to research and is supported by some anecdotal evidence that the author has gathered from conversations with professional designers in the user-centred design field.

However positive conclusions showed that the teams with relevant information produced a greater percentage of effective and far fewer irrelevant ideas, with over half of their ideas being effective and only small percentages being irrelevant to the brief (13% for team three, 5% for team four and 5% for team five, table 18). In summary, the use of user-behaviour information in the early stages of a user-centred design process can be beneficial to the design team if:

- Its introduction is introduced at the right time, so that it is a boost to creative thinking rather than a hindrance;

- It supplements the 'common knowledge' that the designer may already have on the design task or problem;

- It is relevant to the brief, to help focus the team's efforts;

- It is in a format that encourages its use and discussion such as silent video clips and data;

- It is of a sufficient level of detail to be immediately understood and not cause confusion.

6.2.6 Experiment Limitations

The results of any small scale design experiment that uses humans as a principal test subject would of course be subject to limitations. The techniques used for this experiment were devised to counter these limitations and an exploration of their implementation and effectiveness is now needed. In order to critically review the limitations of this experiment the experimental context and control techniques are discussed below.

The context of this experiment covered many issues relating to pre and post-experiment conditions, such as the selection of participants, team balancing and experiment development. Due to the time frame in which this experiment was performed there was a limited amount of physical testing of the procedures and experimental material. Participants could have perhaps gone through some kind of standardised "warm-up" exercises to arouse the incubation process and increase motivation [Svaneas et al. 2004, Kim 2006], reducing any possible fluctuations in results caused by motivation factors. These warm up exercises could then have been used as an additional level of team balancing, forming teams on the basis of individual's performance.

Another area of improvement centres on the initial brief given to the participants, which could perhaps have been clearer and better defined. When asked to design a refrigerator, many teams entered quite lengthy discussions on whether that includes a freezer element. This proved to be an irrelevant discussion that either way, would probably not have affected the results but wasted time and introduced an unnecessary confusion. Also a more rigorous interpersonal relationship test could have been performed to establish any possible problem parings or exceptional friends [Barrick et al. 1998] that could have suggested likely areas of conflict or success and been an additional useful tool for team balancing.

Other concerns surrounded possible reasons behind the considerably greater idea-generation performance of the no-input-control team. Despite the best efforts to balance the teams, within all practical considerations, the Belbin score of Person B in team one was more heavily weighted towards the shaper role than any others taking part and this must have affected this particular team's exceptional performance. This can be seen in the qualitative assessment of their performance. Person B was instrumental in keeping the creative rhythm of the team moving with regular shaping comments every few minutes. They did not stay long on a single subject, moving confidently from one concise idea to another with little criticism as to the idea's effectiveness unless it inspired further ideas. The removal of this person (or anyone with a high Belbin score-concentration in a particular role) from the experiment could have been an effective form of normalisation and an area of future work.

Other factors relating to this are the possibilities that some participants may have been self-selective in their ideas before verbalising them to the team effectively limiting the idea generation. In contrast, other participants may have been speaking their thoughts aloud, in effect performing concurrent verbalisation and increasing the idea count for the team. To counter this, particular instructions for brainstorming techniques could have been given to the teams so that they would all follow a similar approach.

A final point of discussion, relating to context, is whether the participants became aware of the research goals or did they remain hypothesis-blind throughout. This could have been done with a simple post-experiment interview and discussion which would have revealed some additional limitations.

Staying with this issue of hypothesis blindness and possible experimental bias, but moving to the issue of experimental control, the role of the experiment controller was, although highly scripted and limited, performed by this researcher himself and thus not blind to the objectives or the delivery of the information inputs. It is possible that a subconscious level of bias in this researcher's body language or speech could have influenced the results. To avoid this risk it would be better to use an individual not connected to the work and unaware of the ultimate research aim, as was the case with the design experiments of Cross et al. [1996].

In summary the experiment was carried out with a great deal of planning and mitigation of the expected problems built into it. The validity of the results however, could have been improved through a more critical exclusion of 'outlier' participants, some physical testing of the procedure (and supporting materials) prior to the experiment and a hypothesis-blind controller.

Despite these limitations, the insights and conclusions can be used to aid in the creation of a new design process to help designers and engineers reduce inefficient use. This has been carried out and the new design process has been named User-Efficient Design, outlined in the following chapter. This approach could be used with any other energy-using product although the next chapter continues to use the data from the refrigerator studies as a case study.

Research Questions (RQ)		Research Activity	Chapter
Objective 1:	**To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour**		
RQ 1.1	What is poor energy-using behaviour?	Literature Review	2.0
RQ 1.2	How can it be changed?		
RQ 1.3	Can behaviour change be designed?		
Objective 2:	**To create a way of measuring the energy impact of user's behaviour**		
RQ 2.1	What are suitable metrics?	Energy Modelling	4.0
RQ 2.2	How significant is poor energy-using behaviour?	Use Scenarios	
RQ 2.3	How can information on behaviour be collected and turned into useful data?	Observational Studies	5.0
Objective 3:	**To explore how designers might use information on behaviour to design**		
RQ 3.1	How can this information be used to aid the design of products?	Literature Review	6.0
RQ 3.2	How do designers interact with this information?	Design Experiment	
RQ 3.3	How should this information be presented?		
RQ 3.4	What impact will it have on the design output?		
Objective 4:	**To investigate if it is possible to design products so that they can only be used in an energy-efficient manner**		
RQ 4.1	What would such a design process look like?	Participatory Research	7.0
		Design Process Demonstrator	
		Industrial Consultation	
RQ 4.2	Can a product improve the impact of poor energy-using behaviour?	Product Demonstrator	

Answered (Objective 1)

Answered (Objective 2)

Answered (Objective 3)

Research Progression and Chapter Outline

7.0 User-Efficient Design

"Doing better things, rather than doing things better"

- McIntosh et al. 1996

The focus of this chapter is answering the last research objective: Is it possible to design products so that they can only be used in an energy-efficient manner? The lack of existing research in this area, of consumer product design utilising user behaviour to optimise energy efficiency, results in the adoption of a participatory action research approach. This approach, combined with insights from the design experiment develops iteratively the new design method of User-Efficient Design. The following section will provide a brief overview of this evolution and development, highlighting the lessons learnt that will be taken forward into the final design method.

7.1 Evolution of the User-Centred Eco-Design Method

The development and evolution of this design method, as shown in figure 31, followed two parallel activities, the study of user energy-impact and the trial and development of a design methodology.

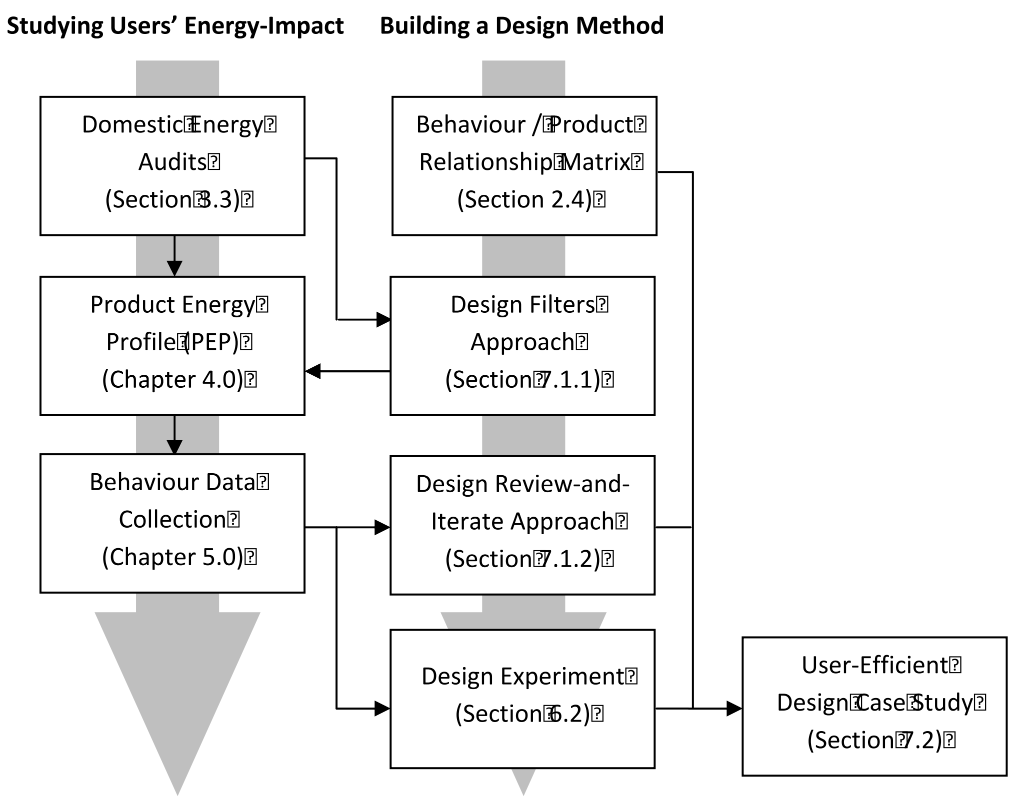


Figure 31 - The evolution of the User-Centred Eco-Design method

The domestic energy audits highlighted, in particular, the kitchen and living room as areas of the home which experienced high energy-use [Elias et al. 2007]. A sample selection of these products was examined with a Product Energy Profile investigation. Following this, detailed user and behavioural studies were undertaken, with the aim being to collect quantifiable data on specific actions and motives of users. During this, increasing complexity of the user studies, the Behaviour / Product Relationship Matrix remained unchanged and stayed as an overarching design strategy and theoretical grounding to any developed design for behaviour change approach. The next two sections will briefly describe these two early design approaches and highlight any key insights that guided the development of the final User-Efficient Design Process. This final methodology will be described and demonstrated in detail subsequently.

7.1.1 Design Filters Approach

The first early design method attempt, the "Design Filters" approach [Elias et al. 2008c], looked at all domestic energy-using products analysed in the domestic energy audits. It then applied theoretical design changes, one at a time, to the design of all the products and predicted the resultant change in energy impacts. Examples of these might be an "automatic off switch" or a "self-adjusting" function to optimise its settings. The aim was to separate those products that could be tackled easily and highlight potential products that would require detailed design analysis. This approach revealed that many products could be improved with only simple design changes and that they shared many common energy-inefficient user behaviours. It also laid the foundations for the Product Energy Profiles, by using methods commonly found in Failure Mode Effects Analysis (FMEA) [Stamatis 2003], suggesting the use of behaviour scenarios and the calculation of theoretical minimum energy values. The development of the Product Energy Profiles preceded the detailed user studies of chapter 5.0 which in turn led to both a new design approach, to be described in the following section, and the design experiment.

7.1.2 Design Review-and-Iterate Approach

The structure of this new approach was kept deliberately simple. In essence new products would be designed in the normal way using a range of different design methods and tools with which the designer was comfortable. These new concepts would then be evaluated against the behaviours they were trying to prevent and the designs would be revised and improved incrementally [Elias et al. 2009a]. By working with a designer, this researcher aimed to observe and experience the design approach in action, as part of a participatory action research study, and understand its implementation and shortcomings.

Concept Generation

For this approach the designer, a final year masters student studying mechanical engineering, used three different design methods, including three selected tools from TRIZ (the Ideal Final Result, Trends of Evolutions and the Contradiction Matrix) [Altshuller 1996], as well as traditional Brain Storming [Osborne 1953] and a Function Means Tree [Cross 1989]. This created in total six new design concepts for a new user-efficient refrigerator, figure 32 (enlarged versions are available in figure 51, Research Appendix 9.4). Each presented concept below was deliberately different to broaden the range of solutions and to avoid design variations of a single theme.

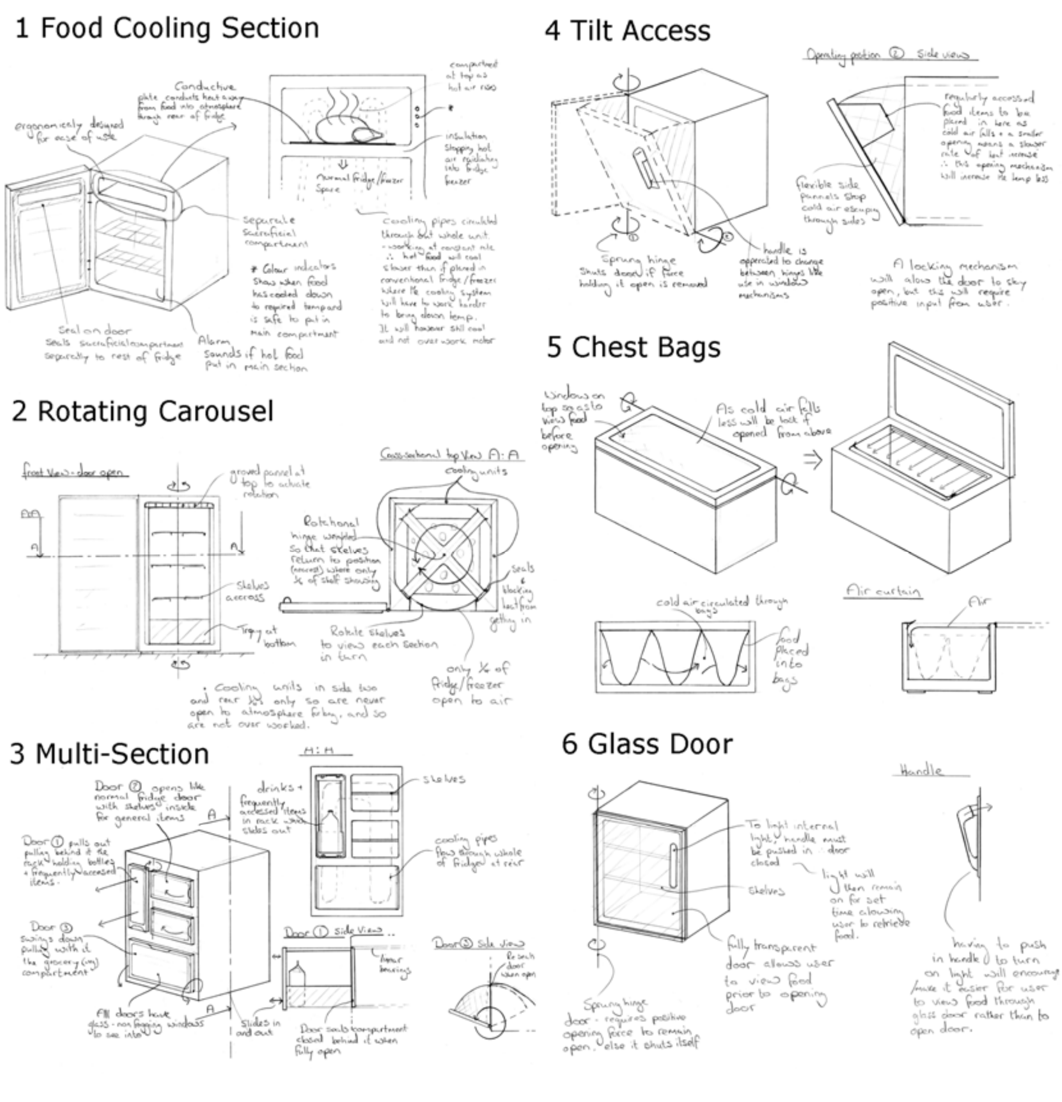


Figure 32 - Six design concepts for a new User-Efficient refrigerator

Looking at the designs that came out of this approach in figure 32, they can be summarised as follows:

- Design one is fitted with temperature sensors which sound an alarm if hot food is placed in the main cold compartment and provides an insulated area for hot food;

- Designs two and three separate the main compartment into different sections so that only a small part is exposed to the warm air of the room once opened;

- Design four alters the hinges on the door of a conventional refrigerator so that in addition to the normal swing door it can also tilt forward. This allows items that are used frequently, such as milk or butter, to be accessed quickly without exposing the whole compartment;

- Design five is a chest-style refrigerator and so does not suffer from the same cold air loss issues of the others and is also fitted with bag sections to avoid cross contamination of food and for ease of food removal;

- Design six has been fitted with a glass door so that users can decide what they wish to remove and can locate it before opening the door in order to reduce the frequency of door openings.

Concept Review and Evaluation

The original design concepts of figure 32 were then evaluated in table 19 against the nine most inefficient behaviours witnessed in the kitchen studies of section 5.2. To do this a reinterpretation of some of the classic decision-support approaches was used, by weighting, on a numerical scale, the significance of the behaviours and multiplying this against the concept's potential ability to reduce the impact of this behaviour.

A score was thus generated for each idea. The potential ability ranges from "Yes", being awarded two points, "Partial" awarded a single point and "No" which is given a negative score of one. If the concept actually makes the behaviour impact "worse" than the current situation, it was given a negative score of two. With these evaluation scores the design process was repeated to improve the original designs and produce a set of designs which perform well at reducing all behaviours.

Observed Behaviour	Weighting	Design Concept 1	2	3	4	5	6
1 Open door to take something out	9	1	1	2	2	2	1
2 Open door to put something in	8	1	1	2	2	2	1
3 Open door to look / search / sort inside	7	1	2	1	1	1	2
4 Leave door open during a task with removed item	6	1	2	2	1	2	2
5 Leave door open to do something not related to refrigerator	5	1	2	2	1	2	2
6 Leave door open to search / sort inside	4	1	1	2	1	1	2
7 Open door to load shopping / multiple items	3	1	1	2	1	2	1
8 Leave door open to load shopping / multiple items	2	1	2	2	1	2	2
9 Leave door open because it's not closed properly	1	1	1	1	1	1	1
	Total	-45	23	82	40	78	45

Does the design reduce the energy impact of this behaviour?

Yes	2	No	1
Partial	1	Worse	2

Table 19 - The original design concepts from figure 32 ranked against the highest impact observed behaviours

These evaluations can be summarised as follows:

- Design one, a refrigerator with a "food cooling section", fared badly on all of the ranked behaviours because its design changes were aimed at users who put hot food into the refrigerator, a behaviour which was not observed during the study;

- Design two, "the rotating carousel", actually made behaviour three, opening the door to look inside, worse. The carousel may make it harder to search inside since only part of the contents is on display at any one time. With only a small section viewable to the user, much time might be wasted spinning the carousel unnecessarily, rechecking the contents and deciding what to take. All this means the door is likely to be open for longer;

- The other four designs all did reasonably well with two designs scoring around 80 points out of a maximum of 90;

- Design six, with the glass door, automatically did well on a range of behaviours as the glass door allowed the user to perform any searching or decision-making behaviours without the need to open the door;

- Also designs which had separate compartments and individual access for each would not expose the whole contents to warm outside air and so reduced the impacts of any behaviour where the door was left open for an extended period of time.

Concept Iteration and Redesign

The designs were then improved to reflect the new knowledge learnt from this evaluation and figure 33 shows the redesigned six original designs (enlarged versions are available in figure 52, Research Appendix 9.4). It is not typical design practice to redesign all the original designs, but by doing so this process has neatly demonstrated an interesting issue that all the original designs have been improved in the same manner. This was done with the simple addition of a self-closing glass door and the division of the main refrigerated compartment into multiple smaller sections.

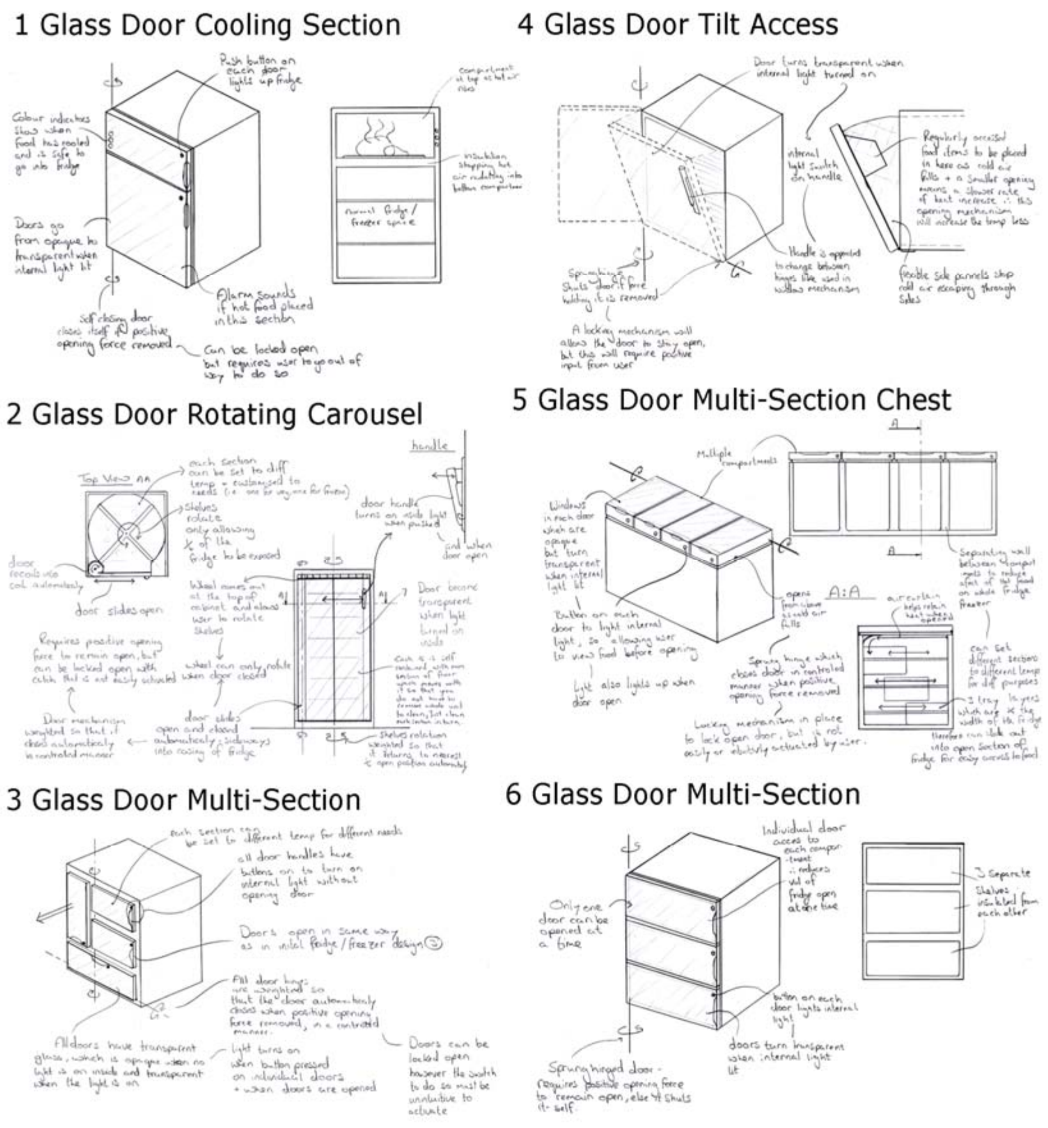


Figure 33 - Six revised design concepts for a User-Efficient refrigerator

This repetition of the same product features reveals a fundamental conclusion of the review and evaluation process: a design is comprised of many different features, each with perhaps a different function, which together form the complete product.

It is these features which are of critical importance rather than the design concept as a whole. This is confirmed when the new designs are evaluated against the same observed behaviours. All six designs score above 70 points with four achieving a maximum score of 90. Even design one, the worst performing design of table 19, is revolutionised with the simple addition of a self-closing glass door, whilst maintaining its unnecessary features. For example any design with a glass door or separate compartments would score well on most of the behaviours regardless of how this was implemented or the weaknesses of the rest of the design.

Process Implications

This design review-and-iterate approach served to highlight two important aspects that this new user-centred design process should take:

1. Information on the target behaviours should be given to designers early in the process so that they do not spend time generating ideas for problems that do not exist. This is supported not only by the creation of design one in table 19 which made improvements to a non-existent behaviour, but also by the conclusions of the design experiment (section 6.2). In this experiment, a clear reduction in the number of irrelevant ideas generated was seen by the teams with user-behaviour information, reducing further as the information became more detailed;

2. Designing product features, targeted at tackling specific inefficient user-behaviours and then combining the best of them into a finished concept is more time-effective than doing complete designs and then revising them.

The following section takes these conclusions and builds them into the new User-Efficient Design Process, which is demonstrated with a design case study that concludes with the prototyping and testing of a new User-Efficient refrigerator in section 7.3.

7.2 Designing a User-Efficient Product

The User-Efficient Design Process proposed here aims to improve the efficiency of a product's use by creating new or revised products which, through their design, lock in desired energy-efficient behaviours, reducing or preventing energy losses. The process builds on the previous two design approaches and also incorporates the studies of user-behaviour to create a single overall user-centred eco-design method for sustainable behaviour change. This new process is outlined here in figure 34 and involves three distinct phases:

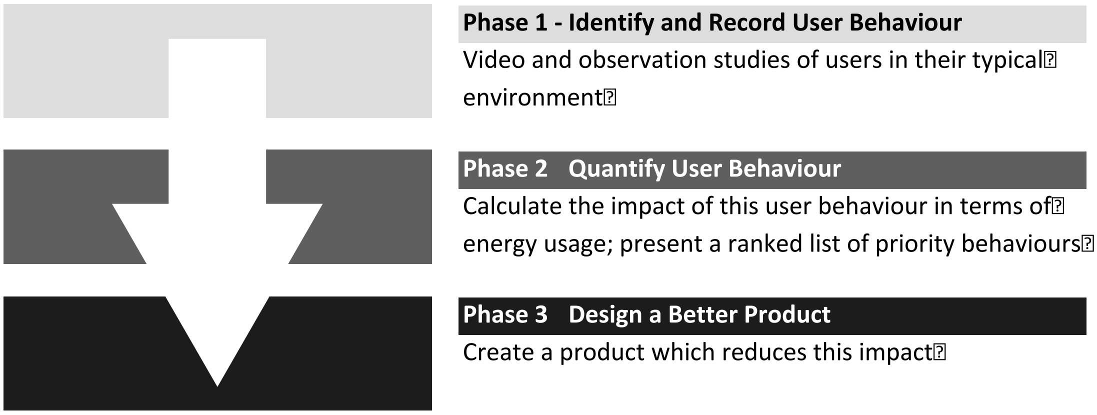


Figure 34 - The three phases of the User-Efficient Design Process

First, the behaviours in question must be identified, observed and recorded, as demonstrated in chapter 5.0. Second, these observed behaviours must be measured and quantified so that the important behaviours can be prioritised. The net benefits, in energy terms, of any new design can then be established against the potential energy savings from reducing or preventing an inefficient behaviour. Lastly, this information should be used to design a better, more energy-efficient product.

This section lays out a framework for how phase three of the User-Efficient Design Process can be achieved and demonstrates it with the case study of designing a domestic refrigerator. Figure 35 shows this framework graphically, sub-dividing phase three into five stages, with the first three concerned with the process of designing product features and combining them into single complete product concepts.

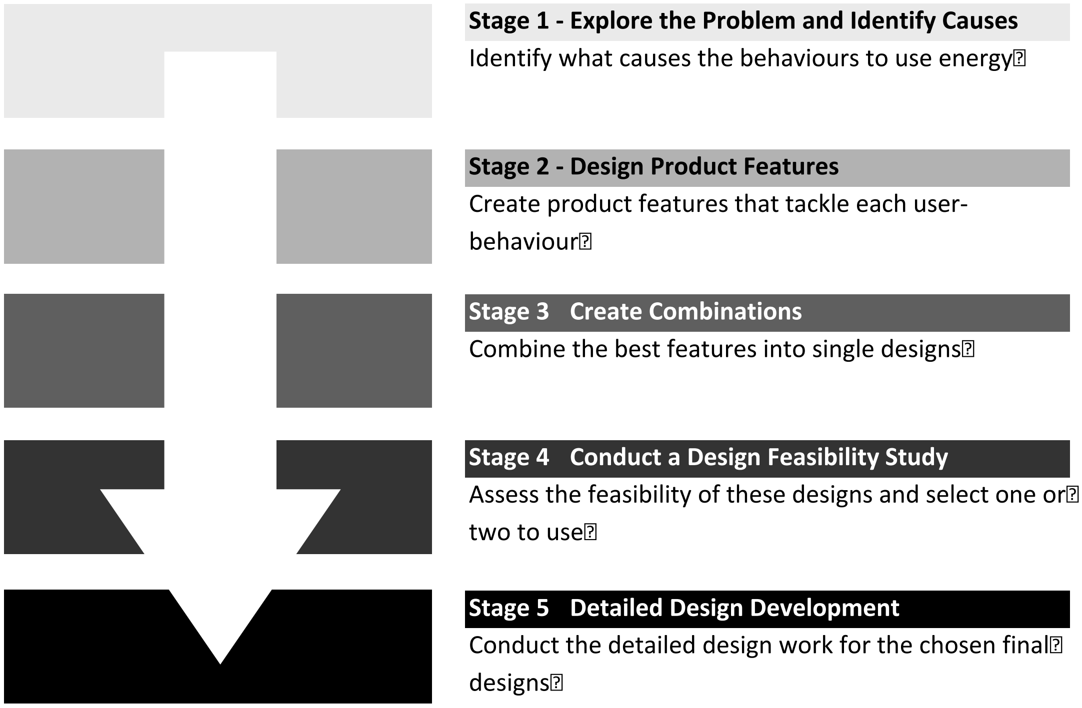


Figure 35 - The five stages of Phase Three of the User-Efficient Design Process

The following sub-sections, 7.2.1 to 7.2.3, outline the creative process of stages one to three, ending in section 7.3 with the development and testing of a physical working prototype for stages four and five. Learning from the insights gained from the design experiment and the previous two design approaches, this section builds and develops the User-Efficient Design Process into a workable design approach that can be used with any energy-using product.

7.2.1 Stage 1 - Explore the Problem and Identify Causes

The first stage of designing a better product is to explore the problem and investigate the reasons behind it. The list of target inefficient user-behaviours has been provided to the designers as the output from phase two, 'Quantifying the User Behaviour'. It is these behaviours that must be explored further. This can be done through a series of simple generic questions, applicable to any energy-using product:

1. **What is the behaviour?**

   The behaviour should be broken down into a sequence of specific, physical actions, which will define the scope of what is to be investigated:

   Open door, find something, take something, close door

2. Why is it energy-inefficient?

A simple description of the physics of what causes the behaviour to waste energy; in the case of the refrigerator, for all of these high-impact behaviours, the "Why" is the same:

Opening the door allows cold air to escape and the contents to warm up. The longer the door is open, the warmer the contents becomes. This warming up must be reduced and the food cooled through the use of electrical energy in a compressor.

3. What causes it?

It is important to understand the user's rationale for each physical action and the physical aspects of the product that actually cause the wasteful energy impact. Listed below are the factors that might have caused this behaviour or explain why it happens:

User-related
- *Not knowing what they want / undecided*
- *Not knowing where it is / trying to find it*
- *Moving things to get something out*
- *Searching contents*
- *Not actively thinking about what they are doing*
- *Taking time to look at items / checking*

Product-related
- *Opening the whole refrigerator*
- *The movement of air*

4. What would prevent it?

This is a list of preventative situations which, if enjoyed by the user or product, would lead to a reduction in some or all of the causes of energy waste. For example, if the user had a better knowledge of the contents, less time would be spent looking and searching with the door open:

Better knowledge of the contents
Better knowledge of the layout / position of items
Better planning of what the user wants to do

Better layout / access

Faster access for common items

Better visibility of contents

Separate contents and access

Restricted air flow

Etc...

Question four starts the creative process by generating situations that, individually or together, address the factors from question three which cause the behaviour to be wasteful. In this case, since the reason for the behaviour being energy-inefficient (question two - the opening of the door), appeared in all of the five highest-energy-impact behaviours (shown in table 11 of section 5.4), many of the preventative situations overlap and are common among different behaviours.

Once these four questions have been asked for each of the key behaviours, stage two can begin, designing product features that utilise these preventative situations.

7.2.2 Stage 2 - Design the Product Features

These preventative situations from question four should now be used as design prompts, creating product features that address each energy-inefficient behaviour. The product features are components that can come together to form a final design (as was the case with the design features in the pilot study described in section 7.1.1).

At this stage, any design technique can be used to assist in the creation of the features. To demonstrate this, this researcher has performed the task, going through the steps for each of the highest-energy-impact behaviours from table 11. This created various preventative situations and in a period of only a couple hours generated 50 relevant product features, shown in no particular order in figure 36 (enlarged versions of which are available in figure 53, Research Appendix 9.4).

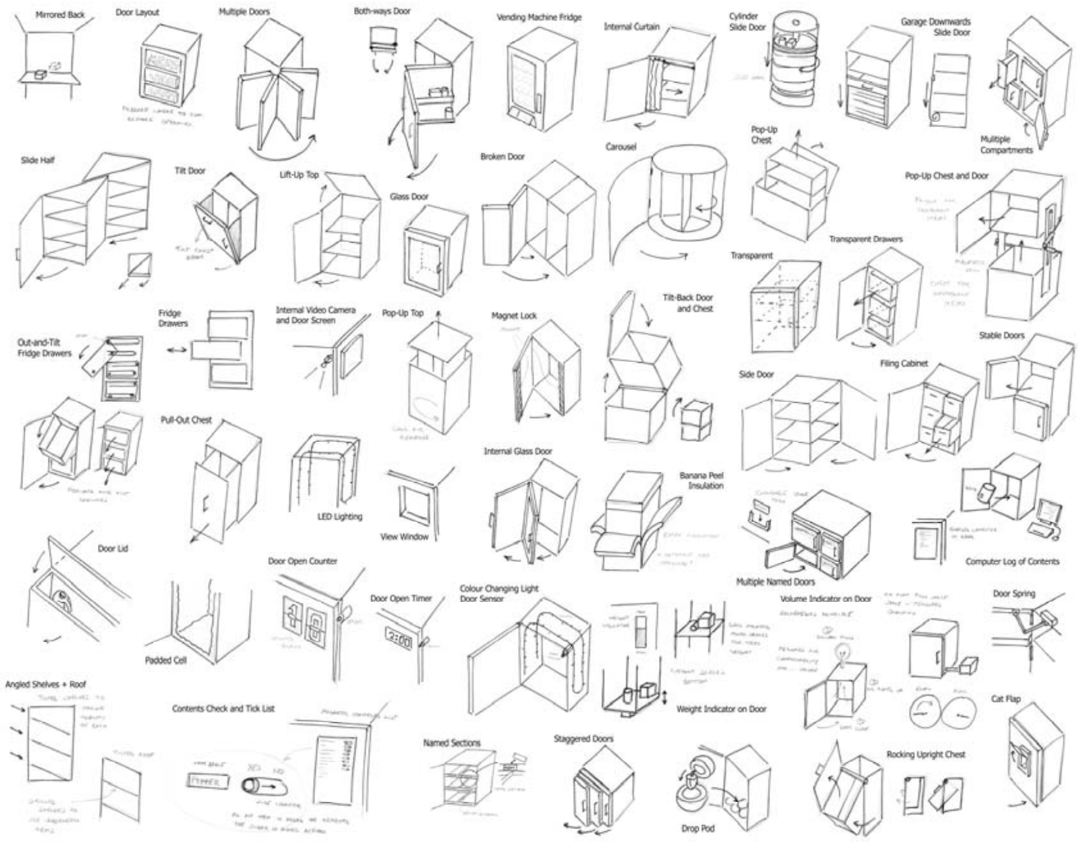
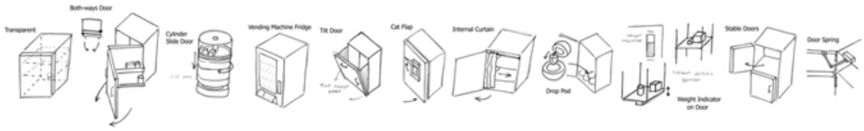


Figure 36 - 50 Refrigerator Product Features

7.2.3 Stage 3 - Create Combinations

From this mass of product features (figure 36) a morphological chart could be drawn up so that the final design could pair up and bring together the best and most feasible features. However, a simple morphological chart does not provide the level of design guidance needed. Due to the nature of people's behaviours and the aim of steering them to a new course of action, it is possible that different features will affect behaviours for better or worse. A feature intended to restrict the flow of cold air and separate the contents might make it more energy-efficient to load and take items, but is reliant on knowing where things are, otherwise it could take longer to find the item required.

Useful questions to consider when assessing the effectiveness of a product feature, in this context of a refrigerator, are: has opening time been reduced or increased? Has the air volume being released been reduced or increased? Has air flow been restricted and, finally, is the new feature easy to use, making the whole process faster? These assessments of the product features can be organised into a review table, shown here in table 20.



Product Features: / Top Five User-Behaviours:	Transparent	Both-ways Door	Cylinder Slide Door	Vending Machine Fridge	Tilt Door	Cat Flap	Internal Curtain	Drop Pod	Weight Indicator on Door	Stable Doors	Door Spring
Open door to take something	✓✓	✓✓	✓✓	✓✓✓	✓✓	–	–	✗	✓	✓	–
Open door to load something (and load shopping)	–	✓✓	✓	–	✓✓	✓✓✓	–	✓✓	–	✓	–
Open door to look / search / sort inside	✓✓✓	✓	✓✓	✓✓	–	–	–	✗	✓	✓	–
Leave door open to do something with the removed item	–	✓	✓	✓✓✓	–	–	✓✓	–	–	✓	✓✓
Leave door open to do something not related to the refrigerator or item	–	✓	✓	✓✓✓	–	–	✓✓	–	–	✓	✓✓

Table 20 - An example section of the Product Features Review

Table 20 shows a sample selection of 11 different product features evaluated against all five top energy-inefficient behaviours. Three ticks is the highest score, signifying that this design is highly effective at preventing or reducing the energy impact of this behaviour, two ticks is good and one tick signifies a slight improvement. A dash means that this design feature has no effect on the behaviour, either positive or negative, and a cross signifies that the energy impact will be worse as a result. This review process could be done by the designers themselves in a review meeting and incorporate any other user feedback they may have.

This adapted morphological design process guides designers to choose only the design features that work best together, addressing each of the highest-energy-impact behaviours in a systematic way. By using a combination of the morphological design approach with reviewed product features it is possible to create numerous effective design solutions.

To demonstrate this approach, three final product design concepts have been created by combining up to four reviewed product features in each. The resulting designs are shown in table 21 and described in turn below.

	Design A				Design B		Design C	
Top Five User-Behaviours:	Tilt Door	Door Open Timer	Internal Glass Door	Door Spring	Vending Machine Fridge	Cat Flap	Both-ways Door	Transparent Drawers
Open door to take something	✓✓	✓	✓✓	–	✓✓✓	–	✓✓	✓✓
Open door to load something (and load shopping)	✓✓	✓	✓✓	–	–	✓✓✓	✓✓	✓
Open door to look / search / sort inside	–	✓	✓✓✓	–	✓✓	–	✓	✓✓✓
Leave door open to do something with the removed item	–	✓	–	✓✓	✓✓✓	–	✓	✓
Leave door open to do something not related to the refrigerator or item	–	✓	–	✓✓	✓✓✓	–	✓	✓

Table 21 - Product Features Review for the three chosen designs

Design A This design (figure 37) combines four product features to achieve a good score for each of the five top energy-inefficient behaviours. These comprise: a forward-tilting door for fast access to commonly used items, such as drinks, whilst opening a conventional door like that of an upright freezer, a door timer to remind the user to close the door more quickly, an internal glass door to allow users to view the contents without cold air leaving and a self-closing door spring to close the door in case they forget.

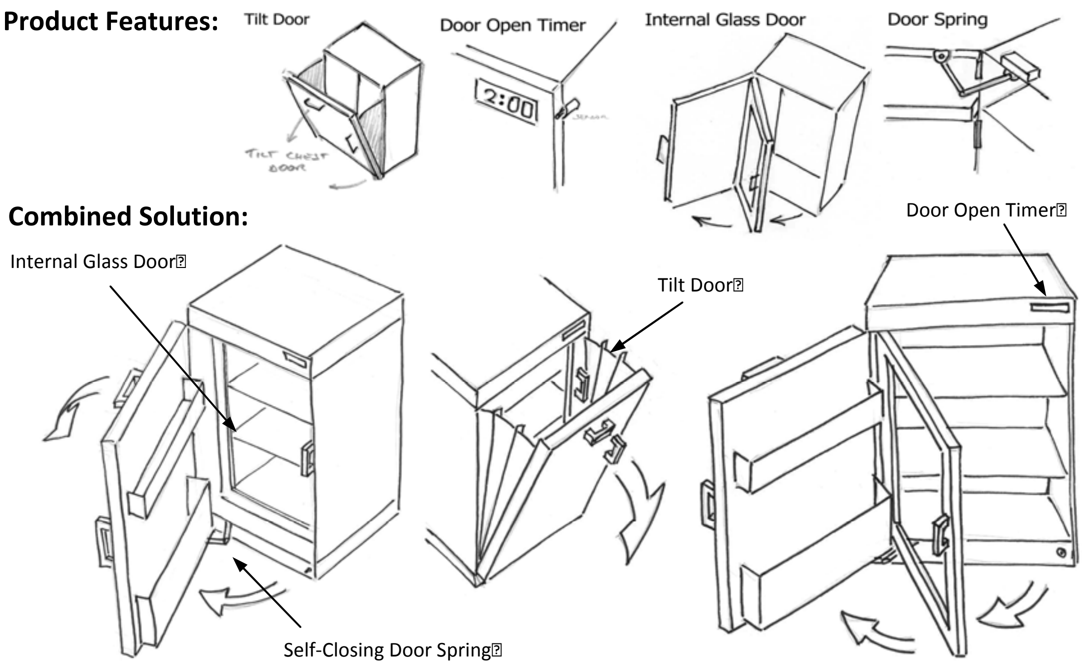


Figure 37 - User-Efficient Refrigerator Design A

Design B This design (figure 38) combines the "vending machine" feature, which scored very highly for four behaviours, with the "cat flap" method of inserting items, to give a combined design which scores highly for all five behaviours. The idea works by items being inserted through the cat flap entrance; as they are entered they are moved to a free space on the angled shelves so that they can be seen. Each space has a number and by typing the number on the keypad that item can be retrieved from the lift-lid compartment at the bottom. These features scored highly because they completely remove the use of a conventional door.

Product Features: **Combined Solution:**

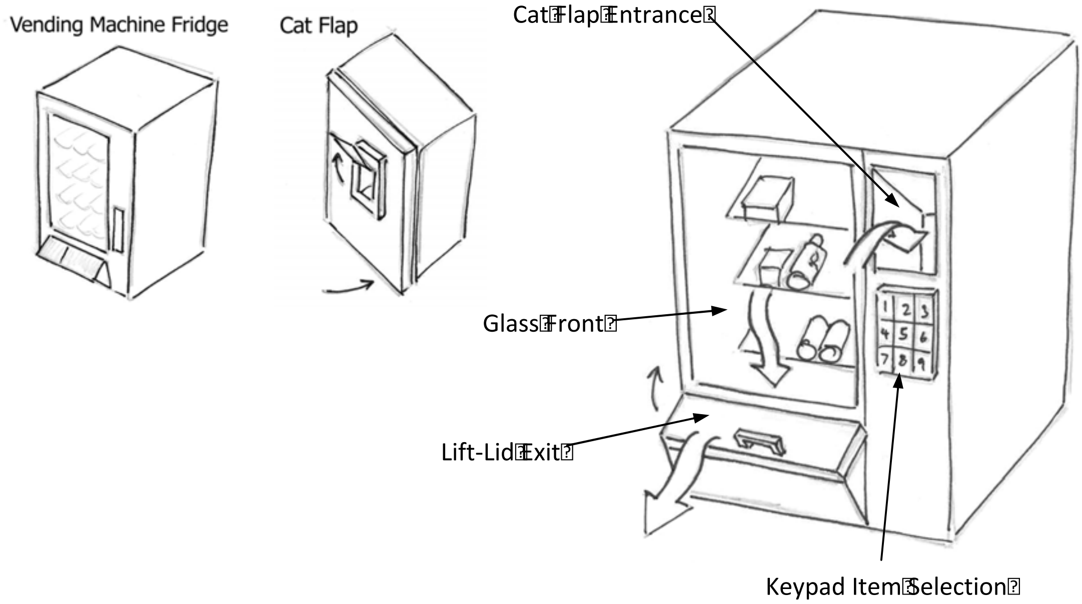


Figure 38 - User-Efficient Refrigerator Design B

Design C This design (figure 39) uses a double two-way hinged door that can be opened to the left to access the "outer" section, an insulated section within the door that houses common items such as milk and drinks. Alternatively it could be opened to the right, accessing the "inner" section. The "inner" section consists of a set of clear transparent drawers that keep air movement to a minimum whilst allowing the user to view the contents.

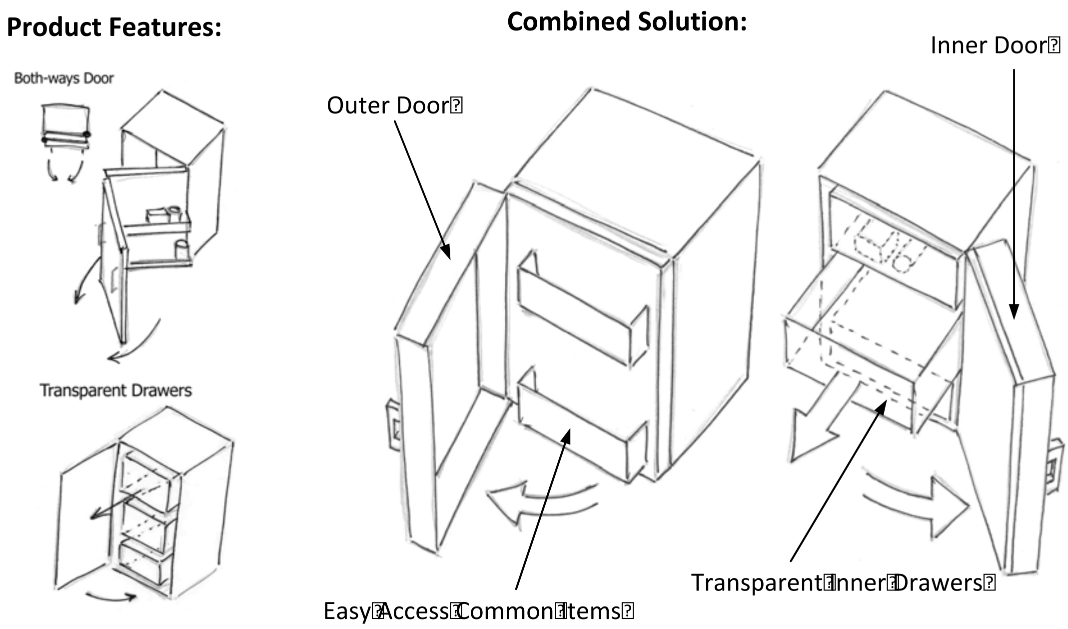


Figure 39 - User-Efficient Refrigerator Design C

7.2.4 Stages 4 and 5 - Design Feasibility and Detailed Design

Stages four and five of this design process deal the design feasibility of these ideas and the subsequent detailed design work that would be needed. As part of this design feasibility and as a valuable validation of the research aims, a full working prototype, based on design A, was created and the effect on users' behaviour was investigated and detailed in the following section.

7.3 Prototype Development and Testing

The prototype refrigerator was based on Design A but, for ease of manufacture, was made without the tilting door and door timer. Also the internal glass door was replaced with an internal clear plastic door. Even without these features the feature review from table 21 still gave a positive score for this design. The self-closing door hinge was also moved to the internal door, in the form of a sprung piano hinge.

The refrigerator from Kitchen Study B was retrofitted with the design changes and then returned to the kitchen to repeat the user study. The internal clear plastic door separated the refrigerator compartment into two: an area for frequently-used items, on the shelves of the original door and a section for items accessed less frequently, behind the clear plastic door. The aim of dividing the refrigerator this way was to reduce the amount of cold air lost when the outside door was opened and thus save energy, reducing the impact of every door opening, regardless of its motive. The following two sections detail how the construction was carried out and the reasoning behind some of the design features, as well as its performance in both energy and user studies.

7.3.1 Development and Construction

The prototype refrigerator was designed to address the top highest-energy-impact behaviours, derived from the earlier user studies:

1. "Open door to take something"
2. "Open door to load something (and load shopping)"
3. "Open door to look / search / sort inside"
4. "Leave door open to do something with the removed item"
5. "Leave door open to do something not related to the refrigerator or item"

By changing the design of the refrigerator it is hypothesised that the impact of these behaviours could be 'designed out' of the product, creating a product which can only be used in an energy-efficient manner. This novel User-Efficient prototype refrigerator would therefore have the following features:

- **A clear internal door** **Behaviours 1, 2 and 3**

  An internal clear plastic door would separate the frequently accessed items from the rest of the refrigerator, preventing cold air from escaping from the latter section but allowing the user to search for the things they wanted.

- **A separate area for frequently used items** **Behaviours 1 and 2**

  The internal door separates a portion of the storage volume into an area that can be accessed for frequently used items such as milk, drinks, juice and butter. Opening the refrigerator to access these items would be quicker and easier and would not affect the rest of the refrigerator.

- **A self-closing inner door** **Behaviours 4 and 5**

  The internal door would also be sprung-hinged so that if the user walked away leaving the door open, it would close itself, reducing overall open time.

- **An on-off timed switch for the light** **Additional Saving**

  As an additional energy saving measure it was observed that the internal light in the refrigerator was a heat emitting incandescent bulb that was rarely needed since its location was often covered by food items. The automatic on-off switch was replaced by an illuminated timed switch which when pressed would turn on the refrigerator light for 10 seconds.

Figure 40 - Prototype Refrigerator Construction

First, the clear internal door was created by building an internal framework between the shelves and fastening the door and sprung hinge to one side, shown in figure 40. The framework was lined with soft insulating rubber to act as a draught excluder when the door was closed.

Secondly, the standard automatic light switch was rewired so that it did not come on when the door was opened, but instead could be activated by pressing a new illuminated switch next to the door handle. This switch turned the light on for 10 seconds or until the outer door was closed.

Finally, the number of shelves in the door, renamed as the “frequently-used-items” section was reduced, the remaining ones positioned higher and instructions given as to the allowed contents for these. This reduction in space available was to prevent it from being used for other non-frequent items and the instructions aimed at stopping frequently-accessed items from being placed in the main chamber. The raised height of the shelves meant access would be easier and thus quicker as the user did not have to lean down so far.

7.3.2 Technical Evaluation

On completion of the construction, it was necessary to compare the technical performance of the new design with the old model and create a measure for its energy efficiency. The changes made only affected the way the refrigerator was used and not the underlying way that it worked. With no change to the technology used or the level of insulation it was deemed that static-laboratory based energy measurements would reveal nothing to suggest an improvement or otherwise.

In addition, comparing energy measurements taken over an extended period of use with those from the new refrigerator could be affected by a number of factors:

- A possible bias in the user's behaviour towards the refrigerator due to their knowledge of the research goals;

- A natural variation in their eating and thus refrigerator-use habits;

- A change in ambient temperature of the kitchen due to the seasonal difference between testing times.

Therefore, the change in internal air temperature was measured when the door was opened in the old refrigerator and compared to that of the new refrigerator. A rise in internal air temperature would reveal that cold air was leaving and being replaced by warmer air, which takes energy to cool. Thus reducing the amount of air change and internal temperature would suggest an energy saving.

The main compartment of the unaltered refrigerator, before any design alteration had taken place, was fitted with digital thermometers and the change in internal air temperature was measured as the door was opened. This was then repeated after the design changes were implemented and the results compared. The temperature measurements for the original, unaltered, refrigerator are shown in figure 41 and show that when the refrigerator door is opened to 90^{O} for a total open time of 5, 30 or 60 seconds, with an ambient air temperature of 24 °C, the air temperature inside takes an average of 10, 17 and 22 minutes respectively to recover.

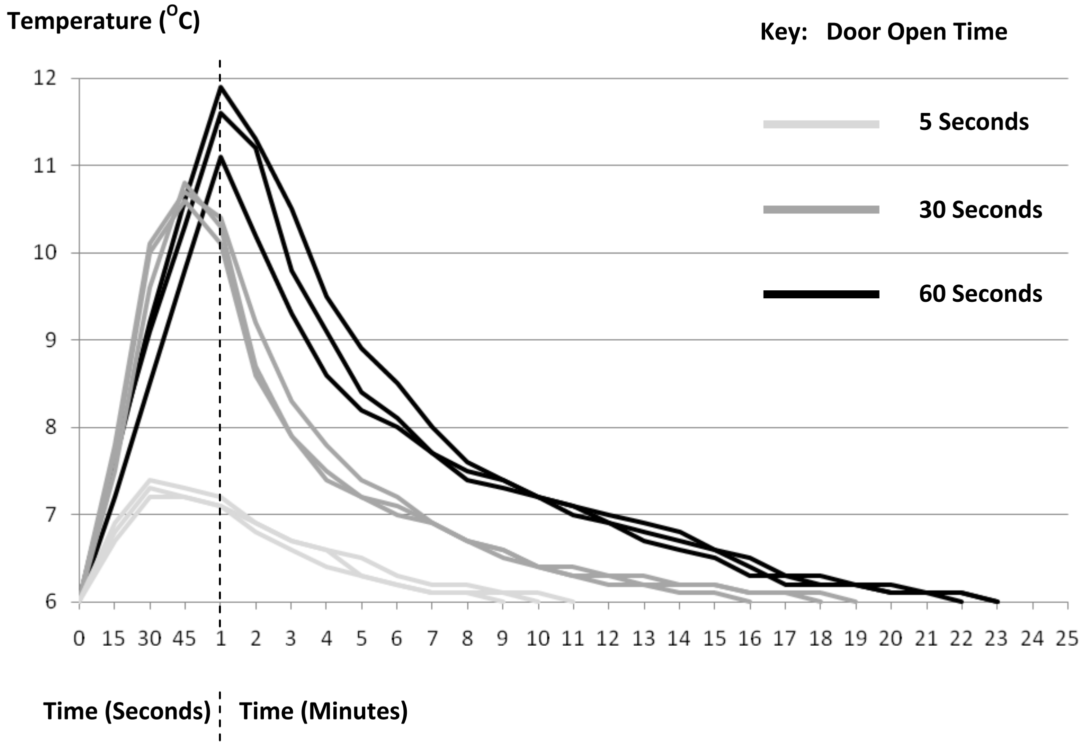


Figure 41 – Refrigerator internal air temperature change when opening the door

This data is supported by research from James et al. [2008], in Research Appendix 9.2.2, which states that it took typically an hour for the internal temperature, of a partially loaded refrigerator, to recover to the original temperature after a five-minute door opening. It also typically took three hours to recover after a 10-minute opening. This considerable increase in recovery time is due to the warming of the contents which then in turn takes longer to recover, slowing the whole process.

The data, from figure 41, suggests that a five-minute door opening would certainly cause the internal air temperature to equalise with the ambient kitchen air temperature. Extrapolating this data, linearly for an empty refrigerator, would suggest a recovery time of approximately 43 minutes ((20 – 3.82) / 0.38 = 43 minutes, for a 24°C ambient temperature). However, this refrigerator, unlike those of James et al. would stay at this maximum recovery time due to their lack of contents retaining any warmth when the door is closed.

Repeating this exact series of measurements for the prototype refrigerator showed no change whatsoever in the internal air temperature of the main compartment. This suggests that no cold air from behind the internal clear door (approximately three quarters of the total internal volume) in the large secondary compartment was being lost. This equates to a considerable energy saving and can be used to make an estimation as to the improved performance when used in conjunction with user behaviour information. The refrigerator was therefore returned to kitchen study B and a new kitchen study and data collection was undertaken. The objective was to record user behaviour and identify the frequency and time duration of openings of the internal door, since it is only opening this internal door that causes significant air flow and thus energy use.

7.3.3 User Operation Evaluation

This user study, named Study C and lasting 10 days, followed the identical set-up and format of kitchen study B from section 5.2 with the only difference being the replacement of the old refrigerator with the new prototype (figure 42).

Figure 42 - Prototype Refrigerator in Use

The data collected from this study was recorded and analysed in the same way as undertaken previously (section 5.3) except with the additional measurement of distinguishing between opening the outer door of the refrigerator and opening the inner door. The results from this study can be seen in table 22 and show that, of the total number of occasions the refrigerator was used, only 52% of those involved the inner door, being only opened on average 15 times a day, compared to 28 for the outer door. 57% of the length of time the refrigerator door was opened, the inner door remained closed

Behaviour Description	Study B (18 Days) Unaltered Refrigerator: Time (seconds)	Frequency	Average Time	Study C (10 Days) Prototype Refrigerator: Time (seconds)	Frequency	Average Time
Open either door in order to...						
Look / Search / Sort inside	993	99	10	485	68	7.1
Take Something	2353	298	7.9	859	139	6.2
Load Something	1662	301	5.5	681	141	4.8
Load Shopping	212	10	21.2	68	3	22.7
Use Something in Refrigerator	55	3	18.3			
Play With	46	2	23	40	4	10.0
Clean	95	2	47.5			
Immediately close	12	4	3	23	9	2.6
Outer door left open because...						
Doing something with a removed item	215	31	6.9	26	5	5.2
Doing something not related to fridge	187	20	9.4	113	15	7.5
Putting things back that have fallen	49	7	7			
Not closed properly	16	2	8			
Outer door open in order to open inner door...				445		

	Study B (18 Days) Unaltered Refrigerator	Study C (10 Days) Prototype Refrigerator
Total time outer door open (seconds)	**5895**	**2740**
Average total time outer door open per day (seconds)	**328**	**274**
Average open time per outer door opening (seconds)	**9.9**	**10**
Total time inner door open (seconds)		**1183 (43%)**
Average total time inner door is open per day (seconds)		**118**
Average open time per inner door opening (seconds)		**8.2**

	Study B (18 Days) Unaltered Refrigerator	Study C (10 Days) Prototype Refrigerator
Total Number of outer door openings	**594**	**277**
Average Number of outer door openings per day	**33**	**28**
Total Number of Inner Door Openings		**145 (52%)**
Average Number of Inner Door Openings per day		**15**

Note: the total number of door openings shown above is not obtained from this data but from a separate count of the number of times the refrigerator was opened and closed, as several behaviours might have occurred in series with only a single door opening.

Table 22 - Times and Frequencies of Prototype Behaviours

An additional new behaviour was noted, that of opening the outer door in order that the inner door could be opened, totalling 445 seconds. The true nature of the reasoning behind this behaviour would not be known until the inner door was opened and an action performed, but since this may pre-empt a series of behaviours it would not be possible to divide this accordingly. This time could be best attributed to a 'looking' and pre-planning element. It is essential for any following action and thus should not be classed as a new source of wasted time but instead is a redistribution of time from another behaviour.

Study C had a similar number of average outer door openings per day, at 28 compared to 33 for the same family in Study B. However only 52% of these outer door openings progressed into additional inner door openings and only 43% of the total refrigerator open time had the inner door open as well.

This means that for 57% of the total time when the refrigerator was opened, the inner door, holding three quarters of the total volume, remained closed, improving the user-related energy-efficiency of the refrigerator by 43% (three quarters of the 57%, a figure that is purely by coincidence the same as the total time the inner door was open).

If this product were to be transposed into Studies A and B, a 43% energy saving would equate to approximately 16 kWh and 35 kWh savings a year respectively, from the total energy usage figure of table 12. These savings could be higher because some refrigerator studies (discussed in Research Appendix 9.2.5) suggest that the users in Studies A, B and C are towards the lower end of the spectrum in terms of the number of door-opening frequencies.

Discussions with the participants of Kitchen Study C revealed that initial scepticism about the usability of the design changes was unfounded as the second internal door was actually very simple and easy to get accustomed to. However, further design changes would need to be made in order for this prototype to become a satisfactory product. The lack of air flow between the two internal sections meant that the air between the two doors took a much greater time to cool and had a detrimental effect on some of the items stored in the door, as butter stayed soft and milk went off sooner. The opening of a vent in the internal door, between both spaces, once the outer door was closed could solve this problem whilst maintaining the energy savings described.

In conclusion the product-led design intervention, rather than an educational or social one, led to a considerable and an enduring reduction of 43% in the user-related energy losses associated with this product. This is a validation of this user-efficiency design theory. For additional verification these results and the User-Efficient Design Process were also shared with five professional designers, from consumer product and eco-design industries and five large international companies in the refrigerator and domestic product industries. Their opinions are described in the next section.

7.4 Industrial Consultation

This research clearly has applications to industry. In order to explore industrial take-up of this proposed user-centred design process, for the energy-efficient design of products, feedback was sought from targeted practitioners.

Five international companies, all household names in the design and manufacture of domestic appliances and refrigerators and five professional designers, from a range on companies, backgrounds and expertise, were consulted. The five companies were asked to provide information on their current design practices and product focus and to comment on the design outputs generated by the process laid out in this research. The designers on the other hand were asked to comment less on the design outputs but more on the design process as a whole.

7.4.1 Company Feedback

On the whole the companies were very receptive and welcomed the approach and design outputs. However, competitive pressures and market conditions prevented many of them from being more forthcoming with information on their activities.

One output from this consultation was that although many of the companies stated an interest in this work and keenness for the final ideas, they reported that financial restrictions and cost implications would be prohibitive for this kind of redesign. A leading cause of this would be the legal framework and eco-labelling system which they all follow.

Manufacturers are legally obliged, under new energy-efficiency legislation, to encourage energy-efficient user-behaviour but if a design does not improve the energy rating of the product then it will have little commercial value. Product features that improve the energy-efficiency of user-behaviour are unlikely to see these benefits in the established refrigerator energy testing procedure and thus would not impact the energy rating of this product. This is because the industry standard energy testing for a refrigerator uses a closed refrigerator in a room with a higher than normal ambient temperature, but the door would remain closed. This raised temperature would test the thermal properties of the insulation and is thus meant to compensate for and simulate door openings [Market Transformation Programme 2006]. However, the result is that the insulation is tested but not design changes that affect use, such as door opening, reducing their value to a manufacturer in a highly competitive and mature industry.

In order for energy-efficiency of user-behaviour to be taken into account, the established energy-testing procedure would need to be adapted accordingly.

7.4.2 Designer Feedback

The five professional designers have all been working as designers for a number of years and were chosen for their expertise and wide exposure to a great range of industries and design backgrounds. They were all asked to give opinions on the design process as a whole so that its acceptance within a professional design field could be gauged.

The first designer, a design project manager at PDD, a very well-respected product design consultancy, gave a rather non-committal response, commenting that their approach would more or less follow the approach outlined previously but may also consider:

- Technical trends, to see what future technologies could be brought to bear;
- Food purchasing habits and trends, for example whether bulk buying will diminish;
- Analogous products.

He also reiterated the point made by many of the companies that cost constraints are often the leading factor. He could see his company using this approach, but with focus groups and user reactions as part of the design feasibility stage. This was because collecting this kind of user-behaviour data and analysing it is time-consuming and expensive.

Another designer, an ex-designer for PDD, who was now working as a design project manager for a different company, found the approach very valuable, clearly showing the importance of user studies and thought the choice of a 'fly-on-the-wall' camera perfect for this situation. Overall this designer was highly enthusiastic about the data collection process, design approach and valuable data saying that he could see it being used in the way it had been presented.

Two further design consultants reacted in a similar manner to these previous two, agreeing to the value of the data collection approach but commenting that it might be too time consuming for them to undertake themselves.

Finally, an experienced design consultant and specialist in eco-design had some high praise for the study, stating in email correspondence that:

> *"This is an excellent piece of work. It drills right down to the behavioural issues surrounding energy use. I'm genuinely impressed. The design of the study is excellent.*
>
> *I would have liked to see the suggested design improvements in more detail and a quick assessment of what is already on the market... I really like the video assessment as it allows you to record activities undertaken with the items. Another method would have been to have used RFID tags but this would only tell you what was removed and for how long. Video is much better.*
>
> *I like the choice editing approach - removing behavioural barriers by design. Overall it's really impressive."*

In summary the feedback from both the companies and designers was positive but non-committal. The companies were not as forthcoming with information as the designers. The industry knowledge and insight into energy standards and market pressures was interesting.

Suggestions to include in this user-centred design process were: an assessment of historic and technology trends; existing products already available; knowledge of supporting industries and technologies as well as other forms of design inspiration and the use of focus groups.

7.5 Chapter Summary

The aim of this chapter was simple but ambitious, to answer the final research objective proposed in this study: is it possible to design products so that they can only be used in an energy-efficient manner?

The response came in the form of creating a new User-Efficient Design approach which took behavioural information of users as its core component. The approach was followed with a product case study of a domestic refrigerator and a series of design alternatives created. Features of those designs were used in a prototype design and tested for 10 days in a family kitchen, comparing the actions and behaviours of the users to an earlier study of the same kitchen and unmodified refrigerator. This created an effective before-and-after case study comparison.

The results of this prototype study, showed a potential energy saving of 43% of the user-related energy impact for this refrigerator, greatly reducing the energy inefficiencies of all the top five energy-inefficient user behaviours for this product. This is, in percentage terms, a considerable reduction in energy use through a simple design for product-behaviour strategy, using the 'Counter' and 'Adapt' approaches of square three in figure 10 in section 2.4. It provides a valuable validation of the theory for behaviour change for energy-efficiency.

Research Questions (RQ)		Research Activity	Chapter
Objective 1:	**To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour**		
RQ 1.1	What is poor energy-using behaviour?	Literature Review	2.0
RQ 1.2	How can it be changed? **Answered**		
RQ 1.3	Can behaviour change be designed?		
Objective 2:	**To create a way of measuring the energy impact of user's behaviour**		
RQ 2.1	What are suitable metrics?	Energy Modelling	4.0
RQ 2.2	How significant is poor energy-using behaviour? **Answered**	User Scenarios	
RQ 2.3	How can information on behaviour be collected and turned into useful data?	Observational Studies	5.0
Objective 3:	**To explore how designers might use information on behaviour to design**		
RQ 3.1	How can this information be used to aid the design of products?	Literature Review	6.0
RQ 3.2	How do designers interact with this information? **Answered**	Design Experiment	
RQ 3.3	How should this information be presented?		
RQ 3.4	What impact will it have on the design output?		
Objective 4:	**To investigate if it is possible to design products so that they can only be used in an energy-efficient manner**		
RQ 4.1	What would such a design process look like? **Answered**	Participatory Research; Design Process Demonstrator; Industrial Consultation	7.0
RQ 4.2	Can a product improve the impact of poor energy-using behaviour?	Product Demonstrator	

Research Progression and Chapter Outline

8.0 Conclusions

The work reported in this thesis has made both theoretical and practical contributions to the field of Eco-Design, specifically, within the growing sub-set of Design for Sustainable Behaviour. A multi-disciplinary research approach was undertaken, bringing knowledge from psychology, medicine, engineering and design fields and using both quantitative and qualitative research methods and studies. This concluding chapter begins with a description of the background and research rationale. The research objectives and questions are restated with the main findings for each being summarised. It finally concludes with some recommendations for further research.

8.1 Background and Research Rationale

A rising trend in the use of energy-using products, a competitive and growing movement for environmentally-conscious design within industrial practice, coupled with clear underperformances of the traditional methods to improve the energy-inefficient behaviours of users, energy feedback, education and incentives have all led to a new approach: designing for behaviour change.

Engineers and designers are succeeding in making great progress in the traditional areas of energy efficiency, improving the underlying technology and improving material performance. However, there is a growing acknowledgement and realisation that "a product can only be as good as its user wants it to be" is starting to emerge. Even the most energy-efficient product will still waste energy if it is used badly or unnecessarily. Whilst methods of educating users as to the impact of their actions, as well as ways that they can improve, are making considerable progress in raising international interest in these issues, there has been a notable lack of action. Persuading users to be more energy-efficient is proving to be harder than expected.

The design-focused strategy developed in this work reduces this burden of persuasion. Instead it seeks to influence, prohibit, counter or adapt to poor and inefficient behaviour through physical changes to the product. At the same time, this strategy seeks to maintain the same levels of comfort and convenience that users have come to expect. This is because any products that are seen, by the customer, to impact on their levels of comfort and convenience will have limited appeal and thus limited commercial acceptance and adoption.

Several researchers, from a variety of backgrounds, are currently active in this area of changing the design of products to steer an environmentally-beneficial behaviour. However, it has been a consistent feature of their work that they tend to focus on qualitative studies rather than quantitative ones (section 2.3) and hence their design suggestions can lack an engineering rigour, perhaps resulting in products that use more energy than the energy effect of the behaviour they are trying to save.

As a result, two knowledge gaps were evident. First, a method for quantifying the energy impacts of user behaviour without which a design team lacks a justifiable focus to their work and no measure of improvement. Second, since no quantified information has been obtained previously, there is a need to investigate ways in which this information should be best used by a design team. The research undertaken was thus structured to follow this logical progression: forming an understanding of the problem and surrounding issues, studying and measuring user behaviours and finally using this in a design approach to create a new product which was tested to validate the theory. The next two sections break down the work into its four research objectives and 12 research questions, summarising the findings and contributions to knowledge.

8.2 Discussion of Findings

The research was set up to investigate four key research objectives and answer 12 subsidiary research questions. Chapter 1.0 concluded with a research map (figure 1) how the thesis was structured to address them. To close the loop on this work the findings are summarised and discussed below in the context of these objectives and questions. The subsequent section details the key contributions to knowledge from the work.

Research Questions (RQ)		**Research Findings**
Research Objective 1:		**To establish the state-of-the-art with regards to reducing inefficient energy-using behaviour**
RQ 1.1	What is poor energy-using behaviour? (Section 2.1)	Energy-using behaviour is any action of a user that impacts on the energy-use of a product. 'Poor behaviour" describes those actions which cause a product to waste energy. It has been found that behaviour is set by fundamental issues within a person's psyche. It is influenced by attitude, values, knowledge, fear, culture, economics etc. It often forms a habit which

		continues long after the issue and the user's attitude may have changed. Pro-environmental behaviour suffers from a number of drawbacks to its implementation: ▪ The intangibility of many environmental problems; ▪ The non-immediate, slow and gradual ecological destruction; ▪ High complexity of environmental systems; ▪ A lack of awareness of the link between energy-use and the environment; ▪ A careless and lazy attitude towards energy use.
RQ 1.2	How can it be changed? (Section 2.2)	Four methods for changing user-behaviour are traditionally used: ▪ Environmental and energy education; ▪ Energy feedback; ▪ Social marketing campaigns; ▪ Economics and financial incentives or penalties. These have been shown to be less effective than hoped. User-behaviour is set in the person's reaction to fundamental psychological issues and can often form into a habit or an unconscious action and thus be hard to change on a conscious level. Parallels can be drawn with the difficulties experienced by medical practitioners in changing people's unhealthy living habits. The impact of their bad behaviour has to be immediate and shocking, with an obvious course of corrective action. However, this "immediate and shocking" situation is exactly the event pro-environmental activists are seeking to avoid. Nevertheless research has shown that people are more likely to adopt energy-efficient behaviours under the following conditions: ▪ Energy-efficiency is viewed in terms of the benefits to the individual, especially in terms of increased thermal comfort or health, rather than as a sacrifice; ▪ Energy-use and savings are made visible with feedback systems, thus providing goals and motives where they did not previously exist; ▪ Information is conveyed in a vivid, salient and personal format including visual modelling of specific actions to be

		taken. Traditional methods for changing energy-inefficient user-behaviour have shown disappointing long-term improvements. Designing behaviour-change into products is a promising alternative.
RQ 1.3	Can behaviour change be designed? (Sections 2.3 and 2.4)	The answer to this question is yes and a growing number of researchers are working on this topic. The Product / Behaviour Matrix created in this research, encompasses all the current design methods providing four key principles for design for behaviour change: **Influence** Based on the idea of scripts and persuasive technology, this approach uses technology to prompt, nudge or encourage a particular behaviour; **Prohibit** Uses the design of a product to prevent an undesired behaviour from happening in the first place; **Counter** A product-behaviour approach that works with the existing undesired behaviour, keeping the behaviour unchanged but now with a reduced energy impact; **Adapt** A second product-behaviour approach, more heavily focused on an intelligent product design, where the product monitors its use and adjusts itself to suit how it is being used.

Research Objective 2: **To create a way of measuring the energy impact of user's behaviour**

RQ 2.1	What are suitable metrics? (Sections 4.1, 4.2 and 4.3)	The energy use of any product can be reflecting in a Product Energy Profile (PEP). This is divided into three constituent parts, each with an energy value: ▪ A theoretical base minimum; ▪ The intrinsic losses; ▪ The user-related losses. The theoretical minimum describes the perfect case, the minimum amount of energy required to perform the product's useful function, assuming a particular product layout and the best technology predictions. The difference between this

		theoretical minimum and that derived from laboratory energy tests, of the product in operation, are the intrinsic losses. This energy could be saved by improving the underlying technology and materials. Any difference between these and the energy used in real-life usage of that product is down to the user and thus could be improved through a behaviour-change approach.
RQ 2.2	How significant is poor energy-using behaviour? (Section 4.4)	It varies considerably depending on the product and the user, but past studies have shown it could be as much as 10 - 36% of domestic energy-use. The results from the three example PEPs for behaviour Scenario A, the more reserved of the two, suggests a likely user-related energy losses are in the region of: ▪ 16% for a kettle (15% from Remmen et al. [2003]); ▪ 24% for a 32" LCD television; ▪ 11% for a 200-litre domestic refrigerator. The argument also follows that these values are likely to increase in percentage terms as improvements in reducing intrinsic losses continue to be developed.
RQ 2.3	How can information on behaviour be collected and turned into useful data? (Chapter 5.0)	Behaviour is defined as an action with a motive. The same physical actions may have different motives which must be identified for any design change to be usable. 'Fly-on-the-wall' video studies, giving time for the studied users to forget about the cameras and run for as long as possible, produce an excellent and rich data source. The time consuming analysis could be accelerated through further research. This raw data can be turned into a valuable catalogue of behaviours each with an energy value.

Research Objective 3: **To explore how designers might use information on behaviour to design**

RQ 3.1	How can this information be used to aid the design of products? (Sections 6.0, 6.1	Behaviour information should be used as a design check to ensure that any proposed design changes will save more energy than the behaviour, they are trying to prevent, uses. Without this fundamental information, the design team is designing 'blind', unaware of the impact of their design or the options available to them. The conclusions of this research state that this information

	and 7.1.2)	should thus be used both in the creative process to stimulate new and applicable ideas and in the design evaluation process to check for an energy improvement. Information used to aid creativity is classically referred to as a design stimulus and can take a huge variety of forms, from written information and data, to music or abstract objects and thoughts. Summarised through the concept of expanding a designer's idea space, the use of stimuli in the creative process would suggest that any information can widen a designer's knowledge base and thus stimulate new ideas and thought processes. In this way this user-behaviour information could be used as a design stimulus, prompting new ideas and improving the creative output of a design team.
RQ 3.2	How do designers interact with this behaviour information? (Section 6.2)	Designers were found to react very differently due to the variation in the format and content of information. For example a video clip with sound kept the viewers in silence for fear of missing important information. This was seen to prevent creativity and reduce interaction within the group. Conversely, the designers with silent video clips continued their design development discussions during the viewing of the clips while remaining actively engaged with the video, pointing, talking and commenting on aspects of it. A second finding with respect to this question was that detailed behaviour data and quantified energy values were seen to be too complex for the designers at this early stage in the design process, causing delays and confusion. It is therefore a recommendation that behaviour information should be reduced in complexity to a summarised and ranked 'hit list' for the creative process, the detail then reintroduced later in the design feasibility stage.
RQ 3.3	How should this behaviour information be presented? (Section 6.2)	Four different formats of presenting behaviour information were tried and tested with conclusions surrounding issues of: ▪ **Timing -** Behaviour information should be provided at the start of the design process. Knowledge of this information would avoid designs that were irrelevant and ineffective; ▪ **Relevance -** It should be relevant to the brief, to help focus

		the team's efforts on the most important issues; ▪ **Format -** The format should encourage its use and generate discussion rather than prevent it. Arguably the most successful information format, in this research, would be summarised and ranked into a 'hit list' of the behaviours which need to be addressed. This list should be combined with short silent video-clip compilations of these behaviours taking place in their natural setting, with no involvement of a researcher; ▪ **Granularity -** It should be of a sufficient level of detail and clarity to be immediately understood and not cause confusion. The detailed quantified values should then be introduced during the design feasibility stage of the product development to ensure any change produced a net energy saving.
RQ 3.4	What impact will it have on the design output? (Section 6.2)	A number of important findings were discovered around the use of information in the creative process. The established key metrics for creative output are an improvement in the number, originality and effectiveness of ideas produced, where effectiveness includes measures of relevance, appropriateness and quality: ▪ **Number of Ideas -** If handled incorrectly, stimulus information can act as an interruption disturbing the team's creative process, removing available design time and reducing the number of ideas produced; ▪ **Originality of Ideas -** Where the design subject is known to the designer, a domestic refrigerator in this case, providing additional information will not necessarily improve the creative originality of the design team. This is of great interest to research and does support some anecdotal evidence from conversations with and the practices of professional designers in the user-centred design field; ▪ **Effectiveness of Ideas -** Designers with relevant information produce a greater relative percentage of effective ideas and far fewer irrelevant ideas, with over half of their ideas being effective and only 5% of the ideas, from the most informed teams, being irrelevant to the brief.

Research Objective 4:		**To investigate if it is possible to design products so that they can only be used in an energy-efficient manner**
RQ 4.1	What would such a design process look like? (Section 7.2)	A new user-centred eco-design process, aimed specifically at improving the energy efficiency of products by designing for a more efficient use (User-Efficient Design) was created, comprising of the following three broad phases: **Phase 1 - Indentify and Record User Behaviours** **Phase 2 - Quantify User Behaviours** **Phase 3 - Design a Better Product** The final phase, designing a better product, could be sub-divided further into five stages: **Stage 1 - Explore the Problem and Identify Causes** **Stage 2 - Design Product Features,** using any creative process the designer wishes. **Stage 3 - Create Combinations.** The effectiveness of these features is assessed against specific behaviours and arranged into morphological design charts so that the most effective features can be combined. **Stage 4 - Conduct a Design Feasibility Study** to select the most promising concept to take further. **Stage 5 - Detailed Design Development**
RQ 4.2	Can a product improve the impact of poor energy-using behaviour? (Section 7.3)	The answer to this question is yes. A prototype domestic refrigerator was designed as part of the research and created to test the theory that energy-inefficient behaviour could be designed out of a product, leading to improvements in the overall energy efficiency. Simple and relatively inexpensive design changes to a refrigerator were tested in a real-life setting for over 10 days. The outcome was a reduction in the user-related energy use of 43% without impacting negatively on the levels of convenience of the product.

The contributions to knowledge are initially summarised in section 1.3.4 and are discussed within the key chapters of this thesis. The following section restates these contributions and sets them in relation to other researchers work in the field.

8.3 Contributions to Knowledge

This research has met a wide range of objectives, answered the related research questions and used various methods from simulated energy-modelling to investigative research, design and prototyping. In summary, the contributions to knowledge from this research are:

- Guiding principles of Design for Behaviour Change;
- Energy models of user impact - the Product Energy Profile;
- A method for collecting data on user behaviour;
- Insights into the use of information in the design process;
- A practical design process for improving the energy-efficiency of user behaviour;
- Insights into the future of efficient behaviour design in industry.

These findings reassuringly have a number of similarities with the work of other researchers as well as novel contributions and differences. It is the aim of this section to discuss these and highlight any key areas of consideration and the wider context of this work.

Guiding principles of Design for Behaviour Change

As with any new field of research, the growing numbers of researchers build on the work of each other, exploring different avenues of thought and uncovering new ground. By doing so, they define new terms and tend to name their work after those terms. This is evident from the large number of different names and titles given to the emerging subsets of design for behaviour change that is listed in section 2.3. As the work continues researchers begin to see the similarities and overlap in their work and develop unifying theories to explain the common approach. This idea of unifying the field of design for behaviour change first began with Lilley et al. [2005] and then continued with Tang et al. [2008a].

However, as was discussed in section 2.3.3, it was shown that the models developed were incomplete and only partially successful. This is due in part to the lack of practical application of the Product Intervention Model [Lilley et al. 2005] (figure 7) and the over complication and lack of clarity in the terms of the Seven Design Interventions [Tang et al. 2008a] (figure 8). In contrast the work presented here in the 2x2 matrix of figure 10 and the accompanying four guiding principles: Influence; Prohibit; Counter and Adapt, is clear to understand, encompasses a wider body of work and suggests simple design strategies to follow.

Energy Models of User Impact - The Product Energy Profile

The energy models of chapter 4.0 are an essential cornerstone to this work and which has been surprisingly lacking from other's research and thus presents a valuable contribution to the progression of this field. Without such definitions, a framework for their use and the collection of behaviour data, it would be impossible to judge with any certainty the merits of any new design or product. This could be used for any energy-using products, from machine design and operator efficiency to cars, building design or domestic goods. Without first establishing this context of user-behaviour it would have been remiss to change the way something was done but now it is possible for this to happen.

A method for collecting data on user behaviour

The method of using hidden cameras to study user behaviour is not a new approach [Brun-Cotton et al. 1995, Elliot et al. 2003, Bowman 1994] and, as will be discussed in the following section on the limitations of this research, has a number of issues that make the analysis of the data lengthy and therefore unattractive as a method. This is especially so when compared to the relatively quick and simple 'Researcher Video' as performed by Tang et al. [2008b] in her study of refrigerator use. However the analysis of the video to create behaviour data (section 5.2) is new and enables designers to focus their work appropriately. What is perhaps required, for future research, is a hybrid approach where hidden video is combined with sensor data, in the product itself. This would in effect make the data 'self-coding' and greatly reduce the analyst's time whilst maintaining the highest levels of investigative rigour and an absence of bias.

Insights into the use of information in the design process

Investigating the use of this information, in the early stages of the design process, shares a common research goal with that of Collado-Ruiz et al. [2010] who wished to explore the influence environmental information had on creativity. They setup a 45 minute design experiment which used 56 students from a variety of backgrounds, some creative and some not and randomised them into 5 different groups. The five groups each had different environmental information, including: a no information control; a newspaper article containing environmental information, an email containing environmental information and two Life Cycle Analysis (LCA) studies. The distinction between these information sets seems slight, although a distinction can be made between the so called "soft" information of the article and email and the "hard", presumably numerical, information of the LCA studies.

Despite a few weaknesses in the research method chosen, such as the use of highly dissimilar participants working alone, the division of these participants into different intervention groups with some containing more participants than others, and the lack of clarity and distinction between the information sets, the results are in line with the results reported in this thesis. The group with no information produced the most ideas suggesting the use of stimuli could be a distraction in these rapid, short time-frame design experiments and that "soft" information with a lower level of detail had a positive output on performance.

A practical design process for improving the energy-efficiency of user behaviour

The User-Efficient Design process has shown that by following its simple phases of identifying the undesired behaviour, recording and quantifying it and then using that as the centre of the subsequent design work, a considerable and long-lasting energy saving can be made. The validation of this theory with a practical application and testing has taken this field of research further than many of its researchers have done before and so establishes a good benchmark for further study. The simplicity and universal nature of these phases and the design steps within the final phase ensure that this process can be applied to a wide range of products and not just domestic white goods.

Insights into the future of efficient behaviour design in industry

The discussions with industry as to the implementation of the User-Efficient Design process revealed enthusiasm towards its goals and results but reservations on its adoption. The reasons for this hesitation are perhaps numerous. Many eco-design strategies are sometimes perceived as providing only conservative incremental changes such as reducing the product's weight or replacing materials with alternative ecomaterials, rather than producing the radical innovation desired by companies [Collado-Ruiz et al. 2010]. The specified reason in this case was: the cost implications of doing so, not from the designers' time or effort point of view but in terms of the increased cost of manufacturing the final product. In the case study of the refrigerator, the changes to the design are likely to cost more rather than less, due to the simple fact that more was added than taken away. This is not necessarily an issue, as the savings in energy terms could make this cost effective.

This point was acknowledged by the manufacturers but they feared that this energy saving would not be reflected in the results of industry-standard energy test and thus would not improve the product's energy rating. Without an improvement in this rating, it is harder to justify the increased cost to the consumer and they feared, rightly, that consumers will not pay for it, despite wanting to be more pro-environmental. This conclusion was supported by Truffer et al. [2001] who found that consumers do not always purchase energy-efficient products despite their stated intentions to do so, 20% of consumers stated a willingness to pay between 10% and 20% more for energy-efficient products, yet actual adoption was less than 1%.

This finding has far-reaching implications for this field. If improvements in the energy rating cannot be shown by the manufacturers in their essential sales material then they have little incentive to pursue them. It is therefore vital for the policy makers, government and non-government agencies who regulate energy efficiency to be made aware of this weakness and redesign the product tests so that the impact of user behaviour is included in future.

8.4 Limitations of Research and Threats to Validity

When conducting research it is important to note any limitations or threats to its validity that may influence the results as part of a rigorous and balanced research methodology. This thesis covered three main areas of primary research and each will of course have its own limitations and considerations that should be discussed. Many of these will already have been mentioned in the appropriate sections of this thesis, as and when the research was first being described, although as a useful summary any significant limitations are repeated and discussed here, predominantly with regard to the user studies, the design experiment and design process evolution.

8.4.1 User Studies

The kitchen studies of chapter 4.0 suffered from a few unavoidable limitations due to the nature of the work. First it was decided to use a non-participant observer research methodology for the observation of natural and unscripted behaviours. Due to the obvious complexity involved and necessary intrusion of the participants' private lives, finding willing volunteers was difficult. There are also serious ethical considerations at stake and so participants were found who were familiar with the researcher and the research objectives. The hidden camera was also not hidden, but fitted in a non-obstructive place. So the limitations of these studies revolve around whether the knowledge of the research objectives and ability to see the camera would influence the results. To answer this, there are two approaches to be taken. The first is a methodological argument as to the areas of weakness and any methods used for their mitigation and second, whether a deliberate change in behaviour would likely affect the overall conclusions of the study.

To address this first point a number of mitigation techniques were implemented, the cameras (and associated recording equipment) were made as inconspicuous as possible, being hidden in cupboards or operating remotely via a wireless network. Next, if possible the cameras were set up and then left in place for an extended period of time before recording commenced. For Study A, this equated to over 30 days of camera familiarisation [Vinten 1994, Anderson 2004] whilst the equipment was being tested and data collection and analysis methods devised. The participants of Study A were also not told which product was being investigated so as not to influence their behaviour towards or away from that product. Finally, due to the location of this study (a domestic kitchen) and the length of recording (9-18 days) it would be difficult for the participants not to use the products in question without incurring considerable personal disruption or expense. This however may not be the case for other products and so serious thought should be given to this issue when dealing with luxury items that may or may not be used at the casual discretion of the user.

On the second point, would a deliberate change in behaviour have affected these results? The results of table 11 would suggest that any deliberate manipulation of the product would have to be lengthy and sustained over some time for it to jeopardise the overall conclusions of the study. The sheer length of the study means that any single disruptive behaviour would need to be a major infringement of the existing behaviour patterns for it to interfere with the results statistically. Also, the aim of the study was to identify typical and common behaviour and so any one-off disruption would need to last a great deal of time to have an impact and could be discounted as part of the researcher's analysis.

What about a continued and sustained slight change of behaviour, such as the conscious effort to not open the door for as long? For this to have been enacted, it would have required a pre-meditative thought process and a continued conscious effort to enforce it. Neither of these is thought to have had a major impact for this product for two reasons. Firstly, knowledge of the product under investigation (in the first study) was hidden from the participants. Secondly, the use of the refrigerator is thought to be habitual for most users, thus making it very difficult to alter consciously in an enduring manner.

8.4.2 Design Experiment

The results of any small-scale design experiment of this nature would of course be subject to limitations and many of these have already been discussed in section 6.2.6. In summary the experiment was carried out with a great deal of planning and mitigation built into it and compares very favourably with the experimental procedures of other experiments of this type.

A critical review by Cash et al. [2011a] of other small scale design experiments reveals that although this experiment has some limitations, they are far less than those of other published work. Cash et al. [2011a] investigate six recently published small scale design studies and experiments, the research methods of which, based on the accounts from the published articles, are highlighted in table 23.

In this review, Cash et al. [2011a] discover that of the six small-scale design experiments published recently in reputable design journals, four do not even use the simplest forms of non-treatment experimental control. Other limitations include the lack of placebo controls, a consistent use of students as a participant body, with numbers ranging from 8 to 82, and a lack of reporting generally on their methods, approaches and limitations.

Study	Summary	Research Limitations
[Corremans 2009]	A pre and post-test design study using 32 students in a single group to assess a design method	No non-treatment control No placebo control Limited consideration of possible confounding variables
[Kurtoglu et al. 2009]	A study using 16 recent engineering graduates to assess the value of a computational approach	No non-treatment control No placebo control
[Lopez-Meza et al. 2009]	A study using 12 PhD students to assess the effects of stimuli on idea finding	No non-treatment control No placebo control Limited discussion of the associated limitations
[Lemons et al. 2010]	A study using 8 students to assess the benefits of model building in teaching	No non-treatment control No placebo control Limited discussion of population history / context Limited description of the methods used
[Collado-Ruiz et al. 2010]	A study using 56 students to assess the effect of information on creativity	No placebo control Limited discussion of the associated limitations
[Cai et al. 2010]	A study using 3 mixed experience participants, looking at inspiration sources using multiple short tests	Very limited description of the participants and limited consideration of how this affects the results Limited discussion of limitations

Table 23 - A review of experimental methods in recent small scale design experiments [adapted from Cash et al. 2011a]

The design experiment reported in this research was specifically designed to outperform these others in terms of both rigour and repeatability. The methods and supporting materials, such as experiment controller scripts, team formation guidelines and procedure are freely available on a new website designed and created by this researcher and Cash:

www.designresearchmethods.com

The aim of this website is to encourage other researchers to review and repeat this experiment, thus increasing the sample size, or to use the detailed experiment-planning for their own purposes. It will also act as a design-experiment resource, containing information and guides on research methods for design research, such as how to create placebo teams.

8.4.3 Design Process Evolution

Limitations and threats to the validity of the User-Efficient Design process are difficult to establish. The use of a Participatory Action Research approach, although may be ideally suited to this kind of research activity [Ottosson 2003, Ottosson et al. 2004], could present a few issues of concern as this researcher is not highly experienced in its use. The way, therefore chosen, to reinforce an assurance of its merits was to test and demonstrate the approach with a physical working prototype and to obtain feedback from industry both on the new product and the method. Both of these approaches were followed although the industrial consultation, despite considerable effort, was unfortunately light in its depth and rigour.

The prototype development and testing proved to be very successful. This activity was a particularly pleasing way to close the research loop and one of very few research projects to achieve this. The re-introduction of a product into the house from where it originated made the observed participants aware of the change. A situation that would be very hard to mitigate but could in future research be addressed by the replacement of several placebo products so as to hide the true research goal. This certainly raises questions of bias in the prototype testing, but similarities in the user habits from before and after the introduction of the new product should go some way to alleviate these concerns.

8.5 Recommendations for Further Research

This research has conducted a thorough examination as to why a design for sustainable behaviour methodology would be beneficial and shown how, in the context of energy efficiency, this could be done. It reveals findings on how behaviour information could be collected, a framework for assessing its impact, the role and effective introduction of information in the design process, as well as a design approach for reducing the environmental impact of products during their use.

The use of theoretical minimum energy values is a powerful tool in guiding design and engineering efforts, without which it would be impossible to know where the focus should be. This concept should be built and developed further. Building a database of Product Energy Profiles for a variety of products both domestic and industrial and conducting similar design activities on a wider range of products so that this approach is not just left in the realm of refrigerator design.

A greater understanding of the role of information in the design process and a further exploration of the idea that information could be an interruption rather than a stimulus would be valuable to the wider design community. There are obvious limitations to the design experiment conducted in section 7.2, particularly the sample size. Repeating the experiment with more designers would be beneficial, taking the insights and conclusions obtained here as a guide for future expectations. The use of a placebo control group in engineering design research is also currently underused and work should be done to explore this further and promote its use. An interesting opportunity presents itself in being able to verify past design experiments by repeating them with the addition of a placebo group to see if new insights could be found.

More work needs to be done to develop and test the User-Efficient Design Process in industry. The data collection and analysis would need to be more time-efficient. Research should be done to establish the minimum amount of data required and whether behaviours could be identified automatically without the use of researcher time.

Lastly, policy makers in government and non-government agencies should be involved in a discourse for the need to consider the user-related energy losses of products in the energy assessments of products that they regulate and monitor.

9.0 Research Appendix

9.1 The Potential for Domestic Energy Savings through Assessing User Behaviour and Changes in Design.

This appendix highlights the results of the energy audits of section 3.3 from Elias et al. [2007]. The results of the energy audit are shown in table 24 below.

	Device	Total Daily Energy Use (kWh)	Number of Items in the Sample
1	ELECTRIC SHOWER	34.246	10
2	COOKER	17.907	6
3	COMPUTER + MONITOR	8.644	11
4	WASHING MACHINE	4.891	6
5	KETTLE	4.709	6
6	OVEN	4.362	6
7	FREEZER	4.083	8
8	FRIDGE	3.773	6
9	HAIR DRYER	1.900	7
10	DISHWASHER	1.875	3
11	HI-FI	1.464	10
12	TV	1.423	9
13	VACUUM CLEANER	1.218	6
14	MICROWAVE	1.040	4
15	VCR	0.970	5
16	TUMBLE DRYER	0.914	1
17	NETWORK	0.864	5
18	CORDLESS HOUSE PHONE	0.768	11
19	TOASTER	0.712	6
20	DVD	0.186	4
	Total	95.949	

Table 24 - Total Daily Energy Use from the Sample Households

Table 24 shows the combined daily energy use of each electrical product, from all six homes, and ranks them in descending order. The most energy demanding items were the electric showers, the cookers and various computers with the accompanying screens and monitors. An anomaly of the study is caused by the small sample size that puts some items much lower in the table than perhaps a more extensive study would show. The top 20 devices from table 24 have been grouped into rooms where those devices are likely to be found in a typical home. From the results, table 25, the kitchen is the single most energy intensive room with an average of 6.41 kWh per day from our six sample homes.

The bathroom comes second on the table with an average reading of 5.71 kWh caused solely by the electric shower.

	Room	Total Daily Energy Use (kWh)	Average Daily Energy Use (kWh)
1	KITCHEN	38.461	6.41
2	BATHROOM	34.246	5.71
3	LOUNGE	12.855	2.14
4	UTILITY	7.023	1.17
5	BEDROOM	3.364	0.56
	Total	95.949	15.99

Table 25 - Average Daily Energy Use Divided into Rooms

Figure 43 shows the same set of data combined with a typical day time profile. The lifestyle of the professional couple shows an 11 hour gap during the day when they are both at or travelling to or from their places of work. A small amount of electricity is constantly being consumed at their home despite their absence due to the fridge / freezer and other devices always being on. This particular sample, the professional couple, interestingly and commendably did not leave many devices on standby and so this constant level of use was less than expected.

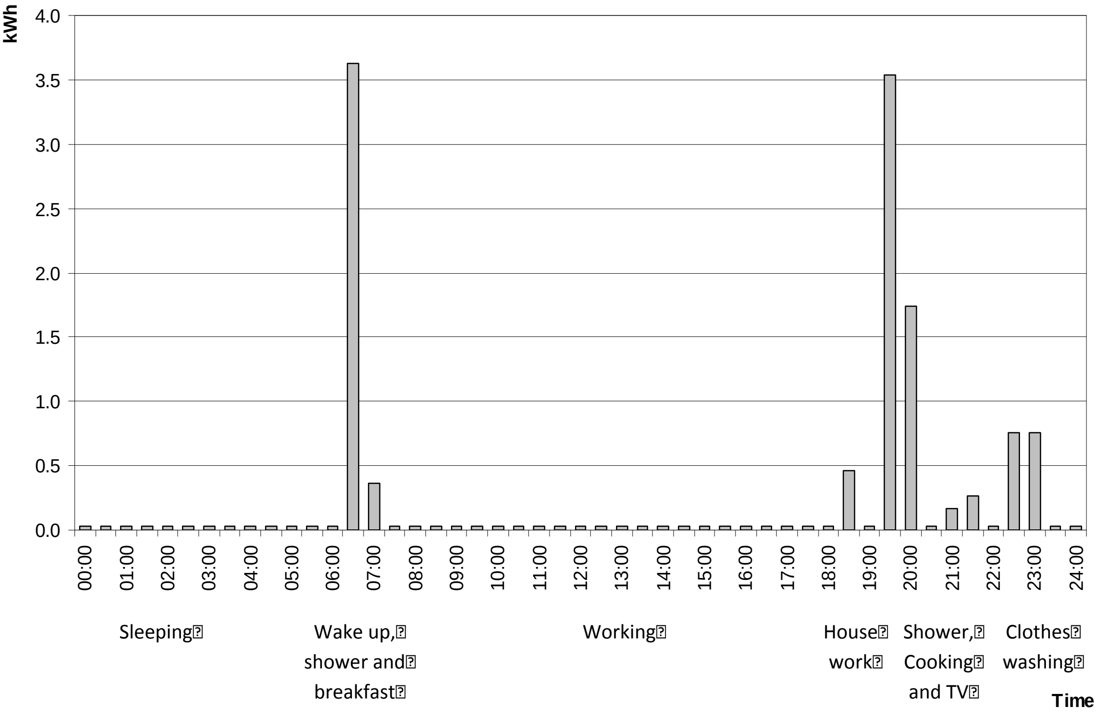


Figure 43 - Time Profile of Energy Use for the Professional Couple

9.2 Domestic Refrigerator Literature Review

The following sections examine each of the six categories of research from the refrigerator literature review of table 6 and each starts with a summary box of highlighted results for quick reference. The six categories were:

1. Operating Temperature and Thermostat Controls;
2. Insertion of Food and Liquids;
3. Surrounding Ambient Temperature and Refrigerator Location;
4. Thermal Efficiency of the Refrigerator Structure;
5. Door Openings;
6. User Behaviour.

9.2.1 Operating Temperature and Thermostat Controls

Most common operating temperature:	6 - 6.9^{o}C	[James et al. 2008]
Operating temperature range:	3 - 8.9^{o}C	[James et al. 2008]
Electricity Increase per 1^{o}C temperature decrease:	3.5% - 6.5%	[Meier 1995]
	7.8%	[Saidur et al. 2002]

In 2008, James et al. produced a report reviewing the operating temperatures of domestic refrigerators and summarising many key findings of research into refrigerator thermostat operation and energy use. In this review the authors cite 21 studies into refrigerator operating temperatures with a combined total of at least 3,424 domestic refrigerators. These were tested and the results showed the most common storage temperature was between 6 - 6.9^{o}C and the majority of results lay between 3 - 8.9^{o}C. This variation in storage temperature can have a considerable effect on energy use; Meier [1995] cites two studies which demonstrate this. The first, in 1991, showed electricity consumption increased about 3.5% for each 1°C decrease in temperature and the second study, 1993, showed an increase of 6.5% for each 1°C reduction. Another study in 2002 [Saidur et al. 2002], showed that energy consumption increased by about 7.8% for each 1°C reduction in temperature. Meier concludes that higher storage temperatures would increase the chances of food poisoning as foods become more vulnerable to bacterial infestation, also commenting that in Meier's opinion the electricity savings from raising the temperature are likely to be offset by the increased costs of accelerated food spoilage.

9.2.2 Insertion of Food and Liquids

Time taken for refrigerator air to recover to original temperature:		
5 minute opening (partially loaded refrigerator)	1 hour	[James et al. 2008]
10 minute opening (partially loaded refrigerator)	3 hours	[James et al. 2008]
Time taken for food to cool from 20°C to 6°C	1 hour	[James et al. 2008]

Information on this topic is not clearly explained. James [et al. 2008] discuss the fact that a 5-minute door opening took one hour to reduce the internal temperature of a partially loaded refrigerator back to the original temperature and an three hours to recover after a 10-minute door opening. This is caused by a warming of the contents and they demonstrate this through the testing of a 4.8cm diameter Saveloy pork sausage which took six hours to cool from 20^{o}C to 6^{o}C. Thermodynamic equations are used by Menninket al. [1998] to show that the energy requirements of inserting 4kgs of food or liquid per day, based on the assumption that the majority of most food types is water, is approximately 27 kWh a year (cooling to 5^{o}C from a starting temperature of 21^{o}C). The EuP document cites two studies that have investigated the impact of inserting and storing hot or cold items in the refrigerator. The first is Böhmer et al., 1998, which states that the insertion of food into the refrigerator uses 10% of its yearly energy consumption and cooling food with a temperature of 50^{o}C uses three times the energy than cooling food with a temperature of 20^{o}C. The second was by Lepthien, cited in the EuP document [Stamminger et al. 2007], who found that thawing frozen food in the refrigerator can reduce energy consumption by up to 26 %.

9.2.3 Surrounding Ambient Temperature of Refrigeration Location

Average ambient air temperature:	20.6^{o}C	[James et al. 2008]
Potential energy savings from reducing the ambient air temperature from 25^{o}C:		
to 21 - 23^{o}C	16%	[Stamminger et al. 2007]
to 17 - 21^{o}C	32%	[Stamminger et al. 2007]
to 13 - 17^{o}C	53%	[Stamminger et al. 2007]

A refrigerator cools the air within it, which in turn cools the contents. Insulation is usually not perfect, letting heat transfer through the walls of the refrigerator out into the room and opening the door lets warmer room air inside. If the air temperature of the room was cooler the difference between the inside of the refrigerator and outside would be smaller and so less energy would be used cooling the contents. James [et al. 2008] found that 72.2% of 252 surveyed kitchens had an ambient temperature between 17 - 23°C, with a mean of 20.6°C. The EuP review states the results of a number of studies into this potential energy saving. One study stated that keeping a room temperature of 21 - 23°C instead of 25°C could save 16%, a room temperature of 17 - 21°C could save 32% and an ambient room temperature of 13 - 17°C could save 53% of energy use. This is supported by two other studies, one which shows that refrigerators use 18 - 19% less energy in a room with a temperature of 20°C instead of 25°C and a second that showed a reduced energy consumption of 47% was possible when the refrigerator was located in a room with a temperature of 16°C instead of 25°C. Interestingly this study then went on to show that a higher temperature of 32°C instead of 25°C increased the energy use by 55%.

9.2.4 Thermal Efficiency of the Refrigerator Structure

Energy loss through the refrigerator walls:	81%	[Mennink et al. 1998]
	60 - 70%	[Saidur et al. 2002]

Although opening the door allows the cold air to leave, it is the thermal inefficiencies of the walls and door that causes the most warming of the contents. In 1998, a series of tests was carried out on a 200-litre refrigerator, a typical size for a European domestic setting, to determine where the largest sources of energy losses were in the device [Mennink et al. 1998]. The product under test showed losses of 81% due to poor insulation in the walls and door, 11% (27.5 kWh) due to addition of food, taken to be 4kgs a day, and 8% (20 kWh) due to door openings, taken to be 24 times a day for 5 seconds each. Saidur et al. [2002] put the value of energy loss through the walls at 60 - 70% of the total energy use.

These energy losses have not been determined by the way the product is used but are dependent purely on the engineering design and materials of the device and are locked into the product at the point of design and manufacture. They are thus intrinsic to the design and construction of the product. Poor insulation, waste heat, unnecessary movement of parts or any other form of un-optimised technical design can all cause what has been classed here as the intrinsic losses.

Engineers have traditionally focused on these intrinsic losses and have enjoyed considerable success in reducing them with improvements in technology and materials science. Since 1980, all models of refrigerator and freezer have reduced their energy use by at least 60% when compared to an A+ rated machine in 2005 [Rüdenauer et al. 2005]. The aim is to see engineers and designers improve how it is used as well as improving what is used.

9.2.5 Door Openings - Frequency of Openings

Average number of openings per day:	40 - 60	[Meier 1995]
	42	[Parker et al. 1993]
	11 - 30	[Laguerre et al. 2002]
	11 - 30	[Saidur et al. 2008]
Maximum number of openings per day:	173	[Parker et al. 1993]

Opening the door and taking things or putting things inside are the primary uses for the refrigerator and an open door has a direct relation to the amount of energy used, but just how often do people open the door? Table 6 shows that there are six studies into this, including two video studies which will be discussed later, one by Tang et al. [2008] and a second by this author. The remaining four studies give a mixed picture, Meier [1995] states that typically households will open the refrigerator 40 - 60 times per day and data from Parker et al. [1993] shows refrigerator openings averaging 42 a day and ranging from 0 - 142 for old refrigerators and 0 - 173 a day for new refrigerators in their study of 1,541 refrigerators in Florida.

These high frequencies of door openings are not however universal. Results from a French survey of 143 households [Laguerre et al. 2002] and results from a Malaysian survey of 104 households [Saidur et al. 2008] differ from this, saying 81% and 67% of their test subjects respectively open the refrigerator between 11 - 30 times a day (table 26).

	French Survey 143 Households [Laguerre et al. 2002]	Malaysian Survey 104 Households [Saidur et al. 2008]
Less than 10 times a day	**19%**	**17%**
Between 11 - 20 times a day	**43%**	**39%**
Between 21 - 30 times a day	**38%**	**28%**
Between 31 - 40 times a day		**11%**
More than 40 times a day		**5%**

Table 26 - Refrigerator Opening Frequency per day Survey Results

The accuracy of this surveyed data has to be questioned as it seems highly likely that people would not be able to give an accurate estimate for average daily openings, perhaps claiming fewer than reality in order to perform well in the survey. Also, no account is taken of the type of household studied; a survey of single men living alone would produce different results to those from a family with several children, for example.

9.2.6 Door Openings - Opening Time

Average opening time:	8 - 19 seconds	[ELIMA 2005]

These results provide an interesting insight into how the refrigerator is used. However, the number of times open per day is meaningless, in energy terms, without an associated time for each opening. The overview from table 6 shows that although there are many studies into the energy impact of a door opening, in which refrigerators are tested in laboratory conditions and the energy use is measured, there are only three studies, including the two video studies, that attempt to measure the opening time from real life case studies.

The first of these three studies is the ELIMA project [ELIMA 2005] which showed a typical range of opening times for refrigerator doors of between 8 - 19 seconds. The second, the video study by Tang [et al. 2008] watched the behaviour of a young family using the refrigerator at breakfast. In this study the refrigerator was opened a total of 21 times and on three occasions the refrigerator was left open for a total of 191 seconds. Unfortunately no data is provided for the length of time open during these 21 times. The third is this researchers own work, which is discussed in great detail in this thesis, but gives the most frequent opening time of 3 seconds and an average opening time of 7.5 seconds.

9.2.7 Door Openings - Energy Impact of Openings

Energy impact of door opening:	0.46	[Mennink et al., 1998]
(Wh / second open)	0.75 - 1.03	[Saidur et al., 2002]
Average energy impact of door opening:	0.68 Wh / second open	

Table 6 shows a clear distinction between the studies that look at the frequency of openings and the time open from real life observations and investigations and those which have conducted laboratory experiments on its energy impact. It is these laboratory results that will be discussed here and will be used later by the author's observation work to quantify the energy impact of the behaviours being witnessed.

The EuP report [Stamminger et al. 2007] cites a study by Lepthien which showed that 20 door openings a day would cause an increase in electricity consumption of between 1 - 6% above the stated consumption of the product. A second study is also cited, that of Böhmer et al., who state that losses due to air change in the refrigerator, as a result of door openings, made up 3% of the total electricity consumption. Unfortunately it is unclear what this percentage represents in actual energy terms as the total energy use of the refrigerator is not mentioned.

The report by Saidur [et al. 2002] also looks at this when they repeat an experiment carried out in two previous studies looking at the energy impact of door openings. The first by Alissi (1987) showed that consumption increased by 6.4% for 20 door openings a day, with a 12 second opening time. The second study by Gimes et al. (1977) showed that energy consumption increased by 6 - 8% for 24 door openings a day, also with a 12 second opening time. Again the total energy-use of the refrigerator is not mentioned but both these studies were conducted on old refrigerators from the 1970s and 1980s and, with the improvements of over 60% in the efficiency of these products over the last 30 years [Rüdenauer et al. 2005], it is likely that Mennink's [et al. 1998] study, with a similar opening frequency but a reduced opening time of 5 seconds would give a similar increase of 8% from door openings, in this case 20 kWh. Saidur's own test found an energy impact of 9Wh - 12.4Wh per 12 second door opening and this is supported by Parker [et al. 1993] who calculate an impact of 9Wh per opening, based on 7% of the total energy use.

Meier [1995], states that energy consumed for 50 openings a day is between 0.25 kWh per day for an energy efficient product and 0.34 kWh per day for older models. However, there is no mention as to the details of this study and how long or what constitutes a door opening. Two more studies, cited by Meier, the first by Peart, which is also cited in the EuP report [Stamminger et al. 2007], says that 40 door openings per day can add between 50 - 120 kWh per year to the total energy consumption. This is not an insignificant amount and is entirely dependent on the user's behaviour.

In summary, it is clear from table 6 that there have been several studies into calculating an energy value for a door opening. Unfortunately, from the published work on these studies, the methods for obtaining the results are often unclear and some important facts, such as open time per door opening are not disclosed. As a result, only two studies provided enough information to establish any degree of accuracy are used and the results are show in table 27.

Mennink et al., 1998	0.46	Wh / second open
Saidur et al., 2002	0.75 - 1.03	Wh / second open
Average	**0.68**	**Wh / second open**

Table 27 - Energy Impact of a refrigerator door opening per second

9.2.8 User Behaviour

User behaviour is the final category of table 6 and is clearly under-researched in comparison to the others. The context of this research refers to the actions of the user when using the refrigerator in day-to-day life. It does not refer to the decision as to where the refrigerator is located or the choice of thermostat settings and temperatures.

9.3 Additional Material from the Design Experiment

This appendix provides information that, although not required for the reading of this thesis, presents additional analysis and experimental rigour that supports the research of section 6.2. As with any experiment relying on human participants for its evidence, results can vary and there is a limit to the amount of experimental control possible. In order to compensate for this and further validate the results, a larger sample size is essential. Consequently all the experimental material and methodology has been made available online by this researcher [www.designreseachmethods.com] for other design researchers to use.

9.3.1 Idea Timelines for all Five Teams

The counted ideas, with their corresponding times, can be plotted on a graph showing the rate of idea generation as the sessions progressed. Figures 44 - 48 show the rate of idea generation for all five teams, in intervals of five minutes. The timings of the four experimental phases have also been marked on the graphs.

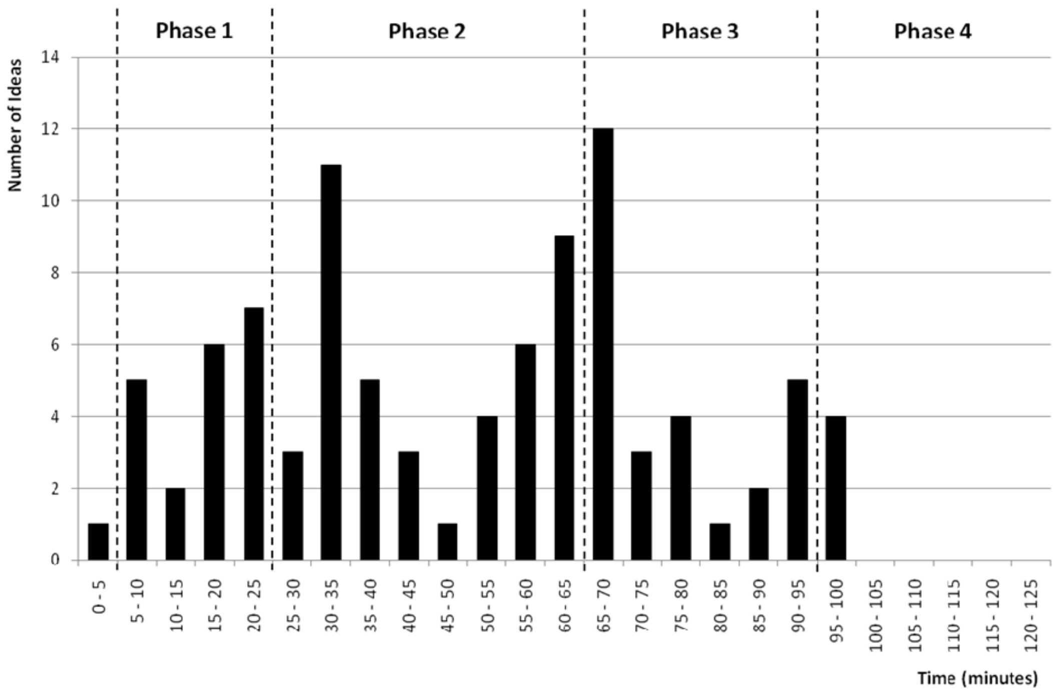


Figure 44 - The number of ideas produced every five minutes for team one

Team one, the control group, figure 44, shows a double peak, with a high rate of ideas, 12 in five minutes, at the start and a second high rate, again 12 in five minutes, towards the middle of the time line. This graph is also distinguishable from the others as it shows a continuous generation of ideas, with at least one idea every five minutes until phase four. Team two, the placebo, figure 45, also had a double peak, producing 16 ideas in a 10 minute period before the placebo video, a break as the video was watched and then a second peak of 10 ideas in the five minutes immediately after the video had finished.

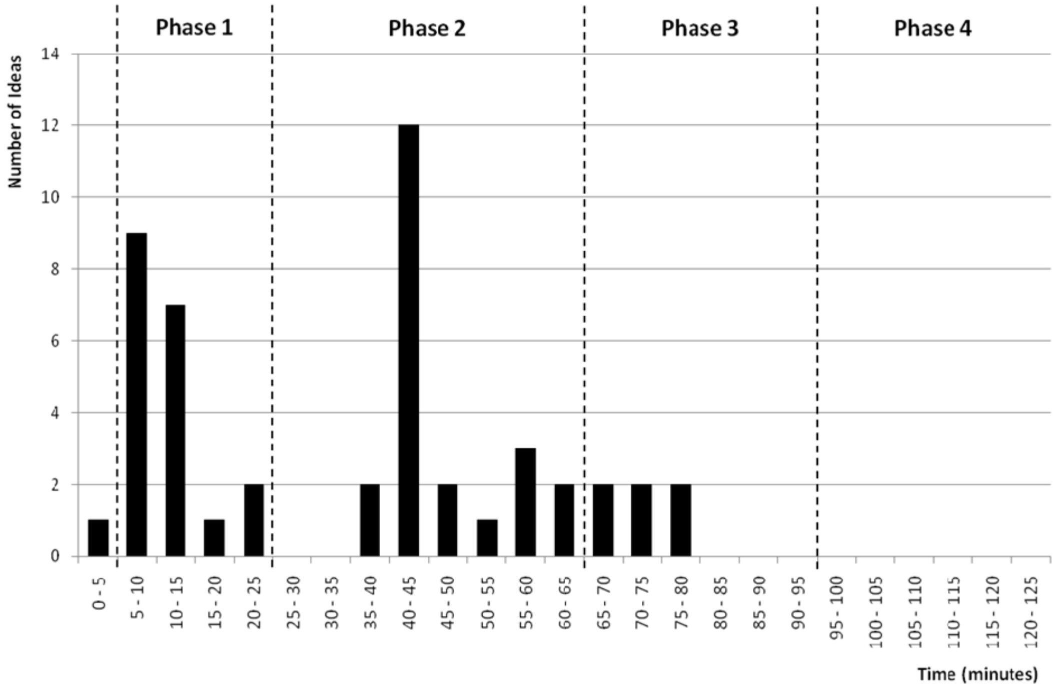


Figure 45 - The number of ideas produced every five minutes for team two

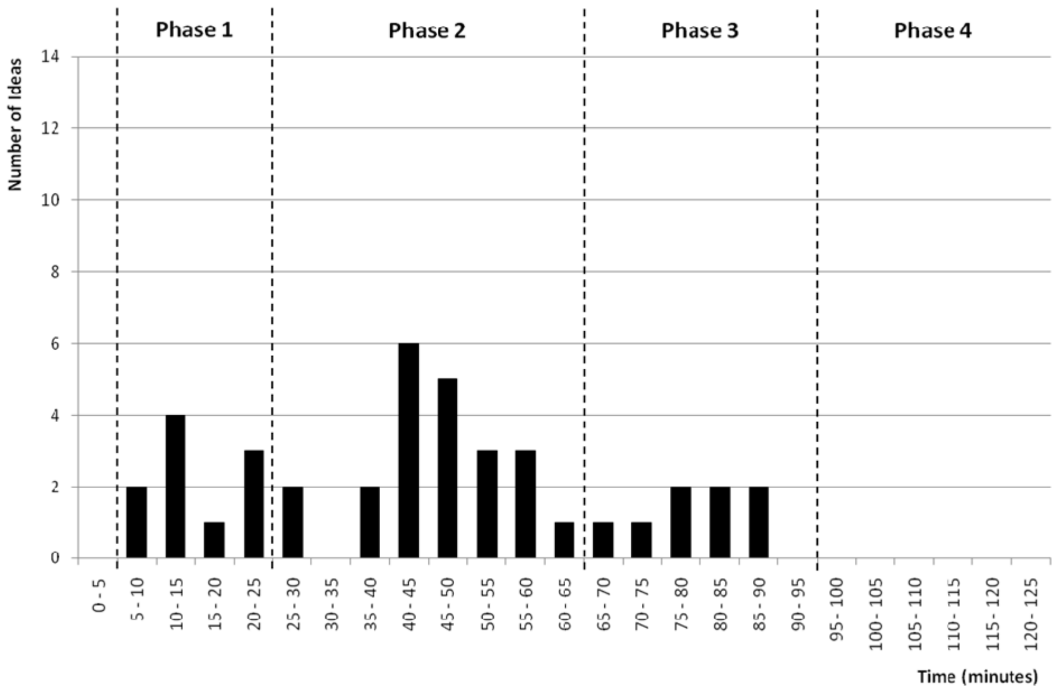


Figure 46 - The number of ideas produced every five minutes for team three

Figure 46 also shows a pause in idea generation of team three at the start of phase two as the video is being watched. The graphs of teams three and four clearly show a reduced overall number of ideas generated compared to the other teams.

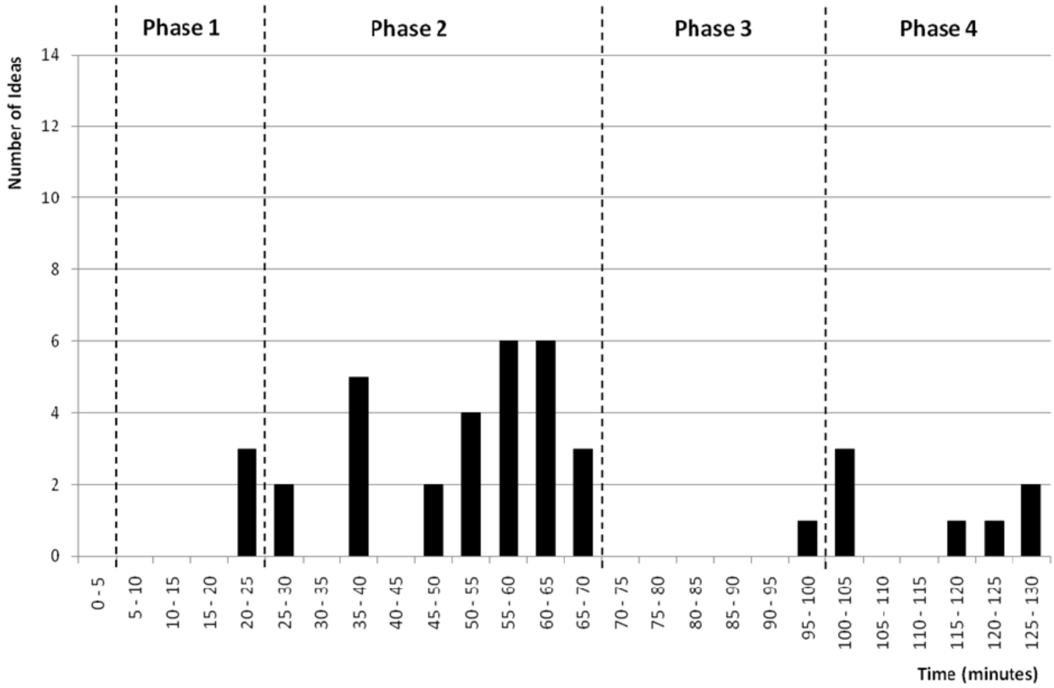


Figure 47 - The number of ideas produced every five minutes for team four

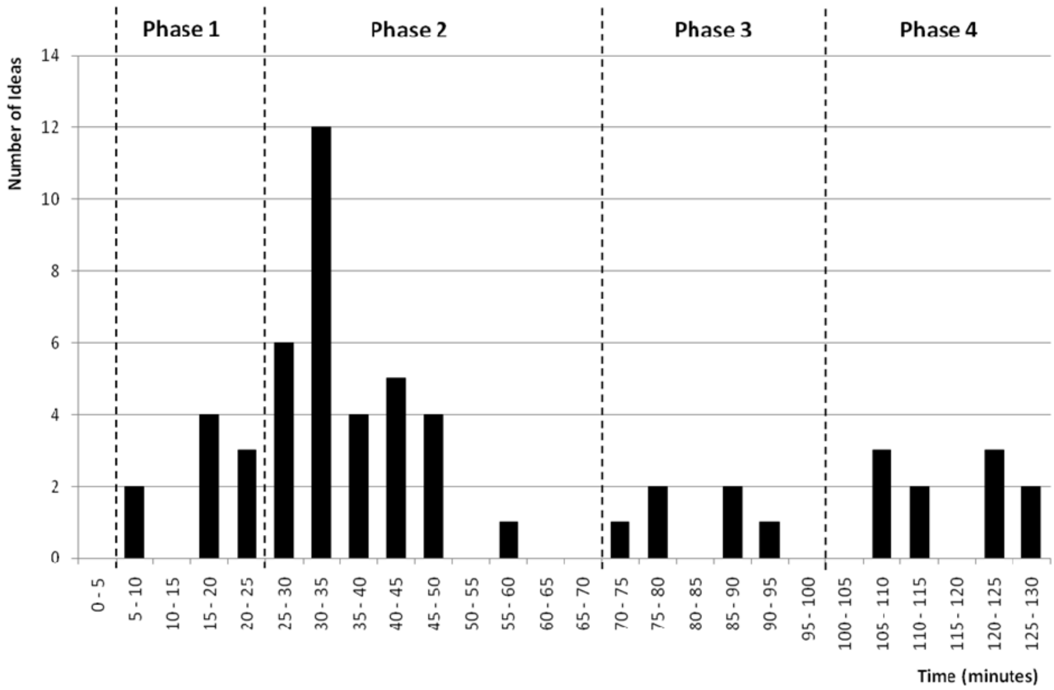


Figure 48 - The number of ideas produced every five minutes for team five

Phase two overran slightly for teams four and five (figures 47 and 48) and hence both these teams have an additional five minute slot, 125 - 130, on the timeline. This was due to the increased amount of time required by the experiment controller to introduce the printed data compared to the video files.

In summary all the teams, who received information, experienced their highest rate of idea generation in the minutes following the introduction of the information, supporting the growing body of research that suggests providing any information is an idea stimulus [Goldschmidt et al. 2009, Perttula et al. 2007, Nijstad et al. 2002].

This could however also be partly explained, for teams two and three, who had lengthy videos to watch, by the passing of a period of time called idea incubation [Aksnes 2006] in which team members were subconsciously considering the design brief for the first 20 or 30 minutes and which naturally came to fruition, with the increased level of idea generation, as shown by team one in figure 43. The results were delayed for the other teams due to consideration of the inputted information, giving the impression of a stimulus effect.

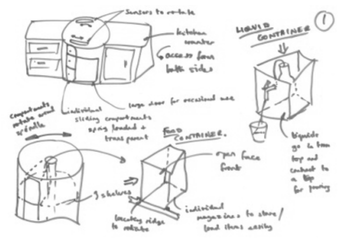
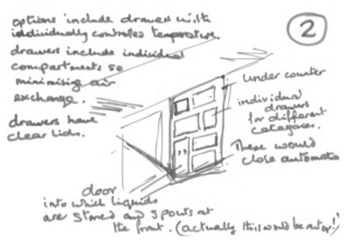
9.3.2 Final Design Concepts

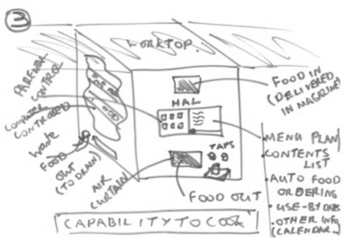
Determining the originality, novelty, un-obviousness [Howard et al. 2006] or other measure of creative flair can be a difficult task to perform and can involve a value judgement by a creative 'expert'. For this paper, originality will be determined by comparing the teams' final ideas with each other.

The final three concepts were all described in sufficient detail to make such a comparison possible and should show a clear indication of creative originality if the concept is not shared by any other team. As can be seen in figure 49, most of the final concepts had a single principal feature which could be used to describe and summarise the concept, but were often realised differently for each team. The glossary in table 28 gives a greater description of many of these principal features which are then used in figure 48 to summarise each concept.

Team 1 "Control"

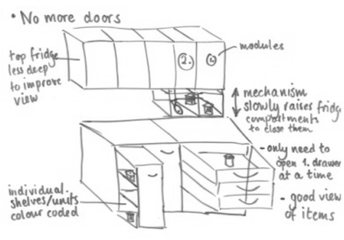
Rotating Carousel + Drink Tap | Multiple Compartments | Artificial Intelligence

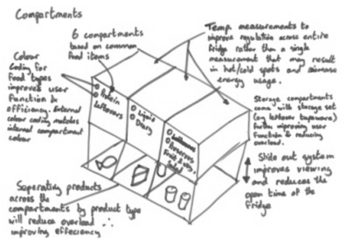



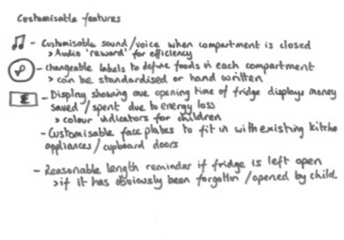


Team 2 "Placebo"

Multiple Compartments | Multiple Compartments | Customisable Display

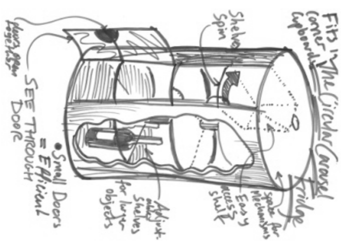


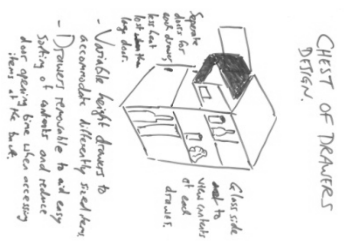


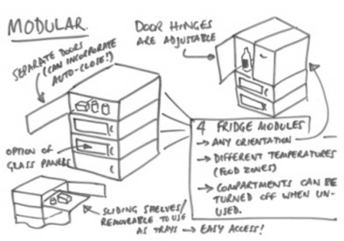


Team 3 "Video"

Rotating Carousel | Clear Side + Multiple Doors | Multiple Compartments

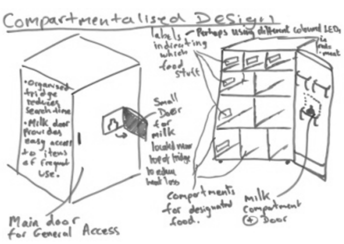


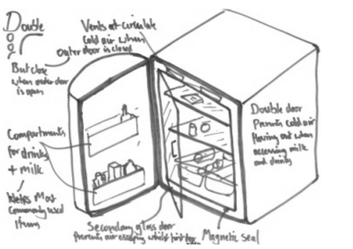


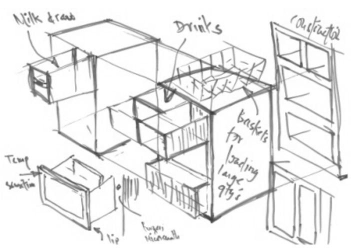


Team 4 "Data"

Multiple Sections + Hatch | Internal Clear Door | Multiple Compartments

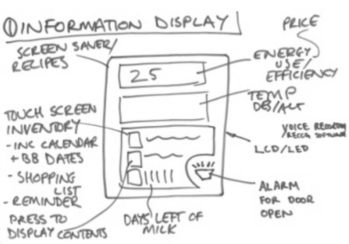


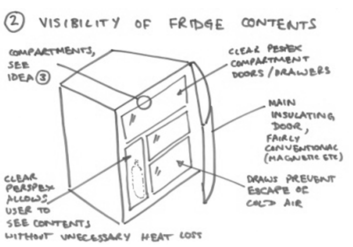




Team 5 "Data + Clips"

Customisable Display | Internal Clear Compartments | Multiple Compartments





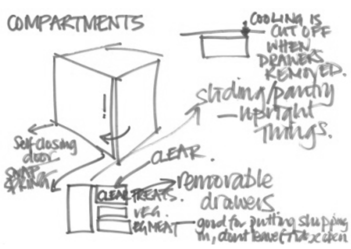


Figure 49 - The final three ideas for all five teams with a summary title and description

Term	Explanation
Compartments	A separately insulated area, accessed independently of the rest
Sections	A single door may open many different sections, allowing cold air to escape from all, but hopes to improve organisation and reduce the time taken to find something
Hatches / Internal Doors	These allow users to access frequently used items without exposing the rest of the refrigerator
Clear	A transparent material that allows the user to see inside
Rotating Carousel	Similar in concept to having multiple compartments but they are accessed each in turn by rotating a shelf
Artificial Intelligence	A fully automated vending machine style refrigerator which not only orders food but can dispose of it as well

Table 28 - Glossary of descriptive terms

Based on a comparison of the final ideas there was no obviously dominant team with many similar if not identical concepts being shared amongst them:

Team One - "Control" Produced an effective carousel concept with integrated taps and liquid dispensers as well as an idea using multiple independent compartments. Their final concept was original but deliberately unfeasible which include automatic food ordering and disposal.

Team Two - "Placebo" Relied heavily on the use of multiple compartments, creating two ideas on the same theme, their final concept was less relevant to the brief, using musical gimmicks and customisable aesthetics.

Team Three - “Video”	Three good concepts, sharing many features with the other teams. One innovative addition was the clear side panel to see right to the back of the refrigerator.
Team Four - “Data”	Three good concepts, again sharing features with the other teams. Interesting features to note are the frequent item hatch for milk or similar in concept one and the internal clear second door in concept two.
Team Five - “Data + Clips”	Two good concepts and one slightly less so, the customisable display would not be as effective as it relies on persuading the user to be more energy-efficient, rather than forcing a change through the physical design of the product.

9.3.3 Qualitative Assessment of Team Performance

This section investigates qualitatively the methods, process and other human factors associated with the teams and this design task, the aim being to uncover any useful insights that may help to improve the implementation of using information during design tasks. All five teams were given no instruction on how to approach the task, only the phases and times of the experiment. As such they were free to approach each phase in any way they saw fit. Although every participant had at some stage in their academic and professional careers undergone either the same or similar design training, each team had a different style and approach. The following sub-sections give a qualitative appraisal of how each of the teams performed and provides context and background knowledge to aid understanding when reviewing the results. Figure 50 represents some of this information graphically, showing approximately the activities the teams were performing at different times.

Blank sections in the activity time lines of the teams, figure 50, clearly shown in the placebo and video teams, indicate periods when the teams were drawing their ideas in silence with no visible difference or development of those drawn ideas from when they had been generated previously in the experiment. Other teams which show a continuous activity line right to the end were continually discussing, developing and generating ideas till the end. From this diagram it can be seen that the placebo and video teams stopped developing their ideas any further when they started the drawing up phase and that the data team generated almost no ideas before the information was introduced. It is also clear which teams underwent a more formal assessment process of their ideas and which teams simply decided which to do very briefly.

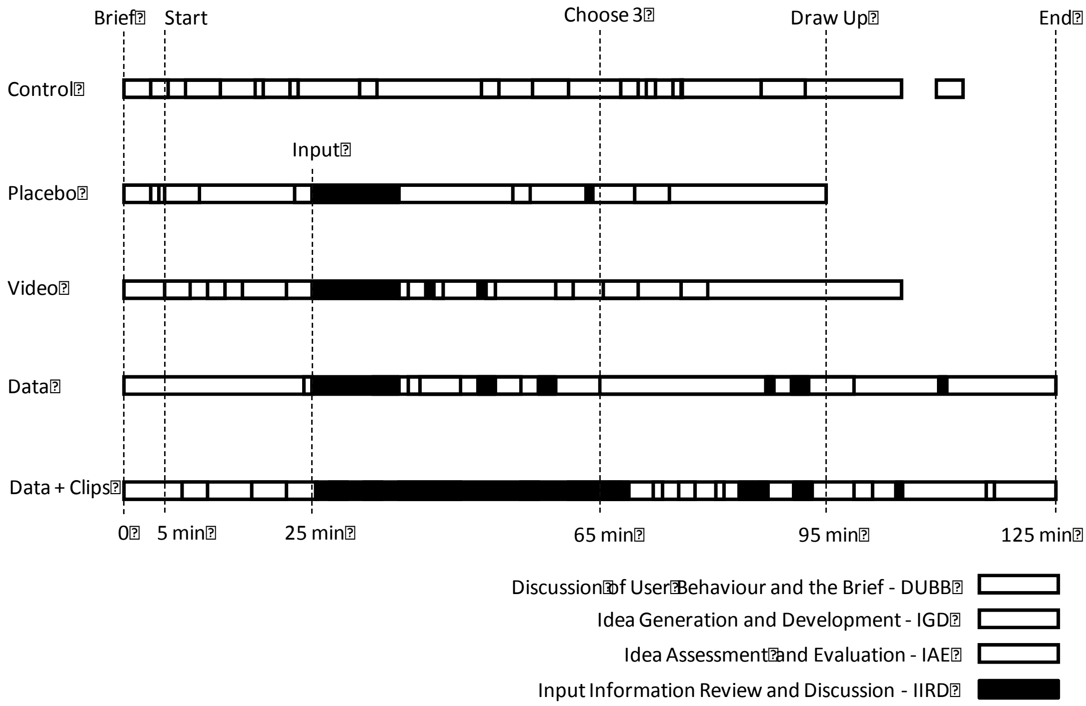


Figure 50 - Team 'activity time line' diagram

Thus the following sub-sections now review the performance of each team using the same activity categories as figure 50, but aims to uncover a greater level of detail into how the teams operated.

Team One – Control

DUBB Discussion of User Behaviour and the Brief

The team began with discussions based on their own experiences and what they believed to be likely inefficient behaviours. For example:

Person B *00:12:17* "Just thinking *what I do at home... If your refrigerator is on the other side of the room from everything you are using, chances are you'll leave the door open and walk across." "Yes I see myself doing that."*

These comments often lead to a product idea, after which they returned to discussions of behaviour and refrigerator usage.

IGD Idea Generation and Development

This team had a relaxed structure, following no formal design methods. However, regular shaping comments from team members, every few minutes, prompted the group to move forward giving them a clear rhythm and momentum to their approach. They did not stay long on a single subject, moving confidently from one concise idea to another with little criticism as to the idea's effectiveness unless it inspired further ideas. The approach was quite similar to the classical brainstorming paradigm of rapid idea generation without criticism or development.

IAE Idea Assessment and Evaluation

An assessment of their ideas again followed no formal procedure, with ideas being compared subjectively to a list of requirements they had generated in the early stages of the process:

Person B	*00:48:03*	*"I think we have to decide on how we're going to access the food and how we're going to know it's in there, these are the two most important things."*
Person B	*00:54:02*	*"So how do you want to do it? Concentrate one on the physical design and one on the technology? Shall we just try and list the features we definitely want."*

With one of their chosen concepts being deliberately futuristic and unrealistic, showing that this group felt unconstrained:

Person B	*01:08:45*	*"Shall we have something nuts [and] high tech?"*

IIRD Input Information Review and Discussion

No additional information was provided.

Team Two – Placebo

DUBB Discussion of User Behaviour and the Brief

The team started relatively well-focused on the main points of the design brief with a statement within the first four minutes of the experiment that:

Person E *00:03:38* *"If we look at all the potential ways of behaviour and just how it's wasted and see if that is an easy way to prevent it."*

Because the team lacked leadership, it did not follow this up, instead becoming distracted with lengthy discussions and developments of simple concepts such as door open alarms. It took them over an hour to cover the significant behaviours that should be designed for. They also did not distinguish between the significance of the behaviours and were vague as to the meaning of the brief.

IGD Idea Generation and Development

The placebo team spent a lot of time discussing minute or insignificant details, writing in silence and slowly recalling relevant stories, showing signs of design fixation [Perttula et al. 2006] on the idea of organising and cataloguing items into separate compartments. They appeared to lack drive to develop numerous ideas and easily became fixated on the detailed technical problems. Ideas were often criticised by the group, with several ideas being stopped before they could be developed further:

Person F *00:44:53* *"Why can't we just have a Perspex door? See what you're getting before you get it." - Person E replied - "It's not very insulating." (this effectively ended this idea chain)*

Others were dismissed in the same sentence as they were proposed:

Person D *00:55:37* *"I don't think we can actually get people to throw things out, we can't have an [ejection of old stuff], you've got to give people some credit for brain power!"*

This critical and judgemental atmosphere, negative thinking and distraction by detailed issues all contributed to hindering the group's creativity reducing the number of ideas generated by the participants.

IAE Idea Assessment and Evaluation

When choosing their best three concepts the team first tried to quantify some of their inefficient behaviours in terms of how long it took to get something from the refrigerator and so on. There was little sign that this related to their subsequent decision-making processes and the discussion quickly moved onto aesthetic points of the appearance. Also rather than selecting or dismissing ideas based on some perceived merits, ideas were grouped together without any clear judgement structure.

IIRD Input Information Review and Discussion

The placebo video was watched only once and referred to rarely. It did not provide them with any specific details and they drew no useful conclusions from it. This also provided tangible assurance that the placebo video was indeed task neutral as designed:

Person D	*00:38:48*	*"Shall we talk about what we got from the video?" "Refrigerator magnets, I noticed the guy had loads of stuff on his refrigerator and I do like that."*

Team Three – Video

DUBB Discussion of User Behaviour and the Brief

This team began by creating a list of things that they considered to affect refrigerator energy-use. Each point often stimulated thoughts and new ideas but discussion of these ideas was kept brief as they continued to focus on creating a comprehensive their list.

IGD Idea Generation and Development

The team spent much of their time in discussion, moving quickly from one subject to another. In the final phase they drew up the final ideas individually in silence, with no further development taking place.

IAE Idea Assessment and Evaluation

The team entered the idea assessment phase with an overview of some of their existing ideas but did not undertake any type of more formal assessment. Instead the team used this phase predominantly to develop new ideas. The three final ideas were simply a progression of their thinking up until this point.

IIRD Input Information Review and Discussion

Watching the video directly generated a few new ideas and although they did not repeat any of the video again, they recalled from memory moments in the video on a few occasions:

Person G	*00:42:45*	*"In the video it mentioned that the top shelf is used the most because it is most convenient."*
Person H	*00:52:34*	*"There were times when she [from the video] went to close the door and left it, but the door opened again and that certainly happens in our house."*

Team Four – Data

DUBB Discussion of User Behaviour and the Brief

The data team used a relatively rigid structure approach, spending the first 50 minutes deliberately holding back on idea discussion as they discussed and evaluated inefficient behaviour, despite some of them becoming impatient with this lengthy exploration and evaluation process:

Person K	*00:32:31*	*"I was happy with that approach [first think of all the inefficient behaviours, evaluate them and then generate ideas] but I wonder if this [data] helping us much more than we realise?"*
Person K	*00:37:54*	*"I am jumping ahead [to the design phase], so forgive me, even if it were [some product feature]" "Well that's the next stage isn't it?"*
Person L	*00:45:28*	*"I would say perhaps at the moment let's just get out the ideas and then rank them against what we have found out [from the data]."*

IGD Idea Generation and Development

New ideas kept cropping up during their behaviour evaluation process but it was not until they decided to look at each behaviour in turn after approximately minute 50, that idea generation began at a rapid pace. This ideation session ended as rapidly as it had begun less than 20 minutes later, having developed 22 ideas in that time, at which point they chose to evaluate the ideas they had and select the best three.

IAE Idea Assessment and Evaluation

To choose the best three ideas a lengthy and detailed evaluation process and assessment matrix was undertaken, lasting approximately 30 minutes. Decisions were then based on their own subjective views of improvement potential, technical feasibility and the behaviour data provided.

IIRD Input Information Review and Discussion

When the data was introduced it became immediately obvious to them that it could save a considerable amount of time by providing them with answers they were about to seek. However, one team member was at first sceptical of its merit and prevented the group initially using it, continuing with their speculative behaviour discussion for a further 20 minutes. During their creativity phase they referred back to the data many times.

Team Five – Data + Clips

DUBB Discussion of User Behaviour and the Brief

This team immediately started discussing behaviours and spent approximately 10 minutes establishing user personas for the target audience and then a food matrix for a typical day. The aim was to predict what products would be likely to be removed and replaced in the refrigerator. The team quickly listed the main inefficient behaviours which were then confirmed by the data and video clips.

IGD Idea Generation and Development

This group had a great deal of discussion and produced a considerable number of sketches. Ideas were generated throughout the experiment but the majority were produced during the 10 minutes following the introduction of the data when the team decided to brainstorm in silence. The ideas were then discussed and compared which prompted further development and new concepts. The team continued to create ideas right until the end of the experiment.

IAE Idea Assessment and Evaluation

The team created a list of all their ideas and then each participant highlighted the ones they thought were the best. This prompted a discussion about combining different features and new ideas appeared as problems with some ideas were exposed. From this list the team assembled their three final designs.

IIRD Input Information Review and Discussion

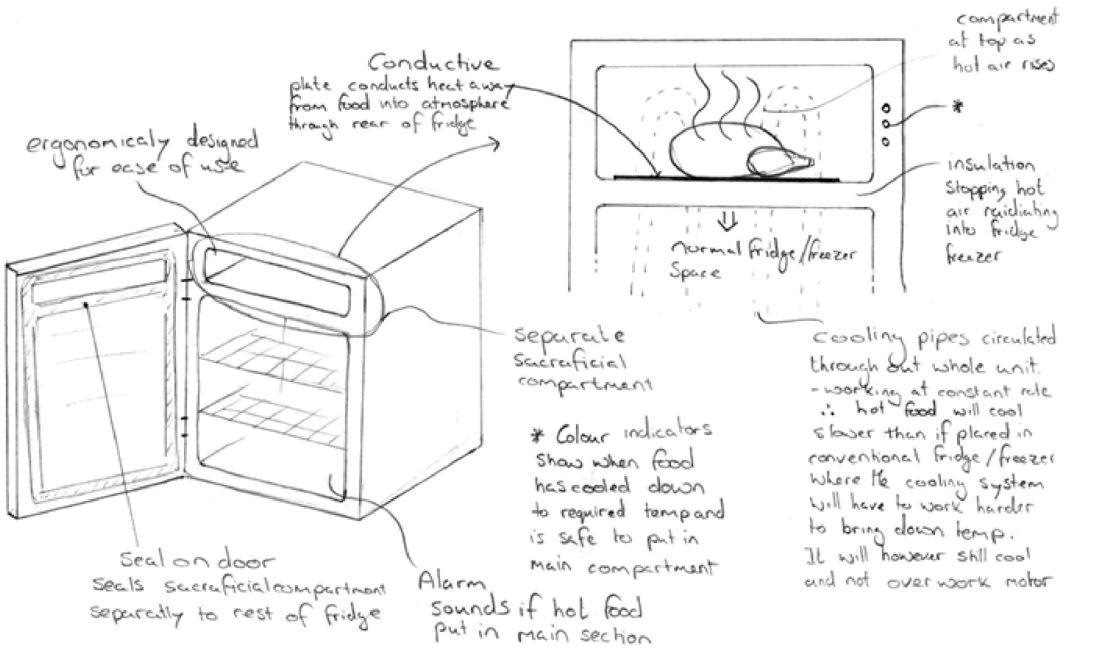
The data and video clips were provided and after reviewing the data over a few minutes they decided to brainstorm in silence. Ideas were then discussed and developed as they watched the silent video clips:

Person O	*00:53:19*	*"It's open because he wants to look in it, so the clear door... He doesn't want to bend down and look he just wants to look down."*
Person M	*00:54:42*	*"She is being pretty indecisive about what she wants."*
Person O	*00:56:13*	*"Look at that [Refrigerator left open], it's been left open, she's gone out of the room."*
Person O	*01:13:59*	*"Bearing in mind the videos we watched, what I think one of the best ideas has got to be, so that you can see into the refrigerator and decide what to take."*

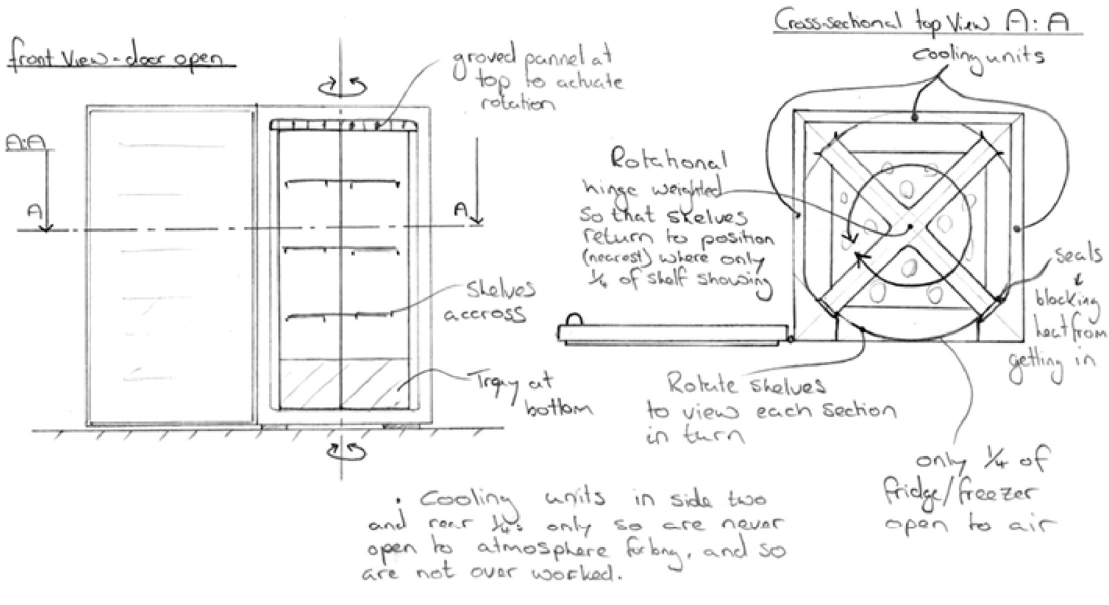
9.4 Enlarged Images

Figure 51 - Enlarged - Six design concepts for a new User-Efficient refrigerator

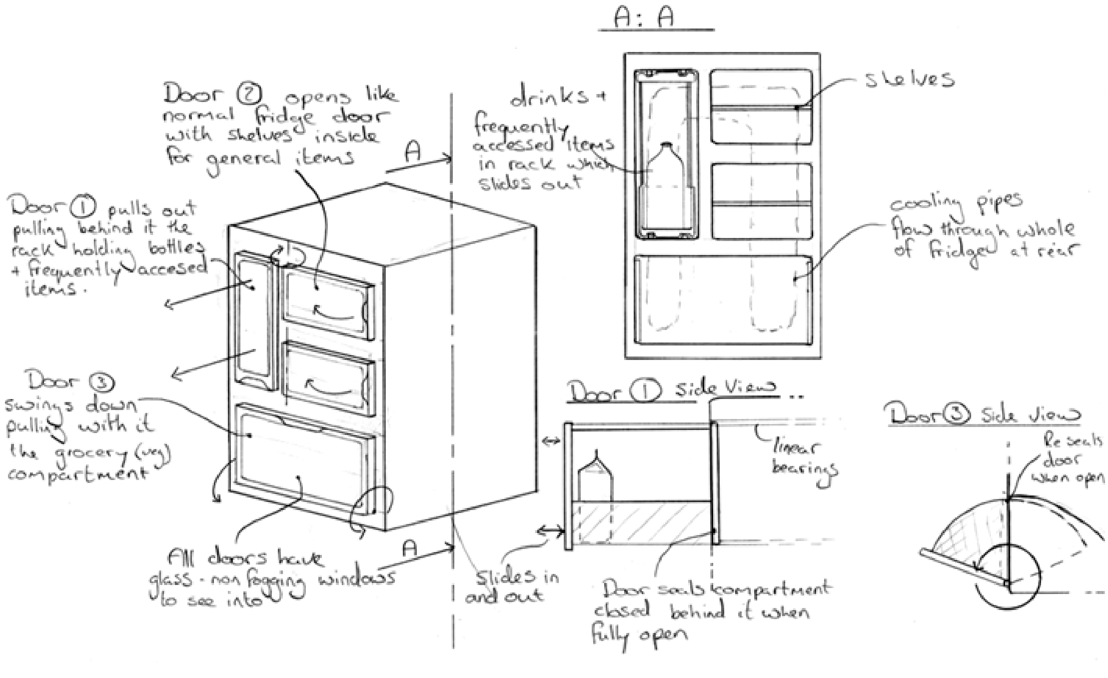
1. Food Cooling Section



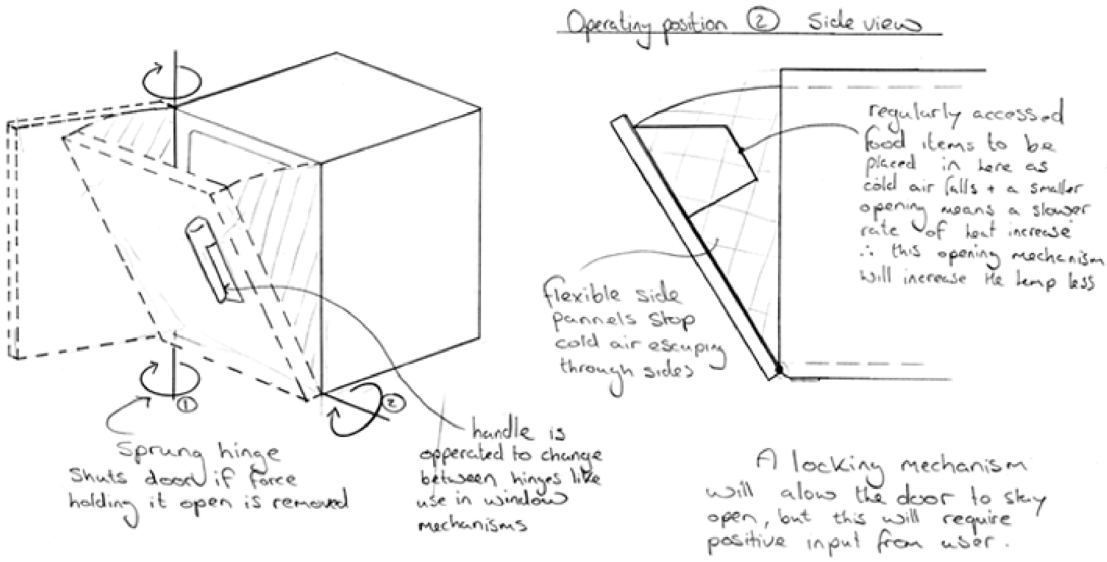
2. Rotating Carousel



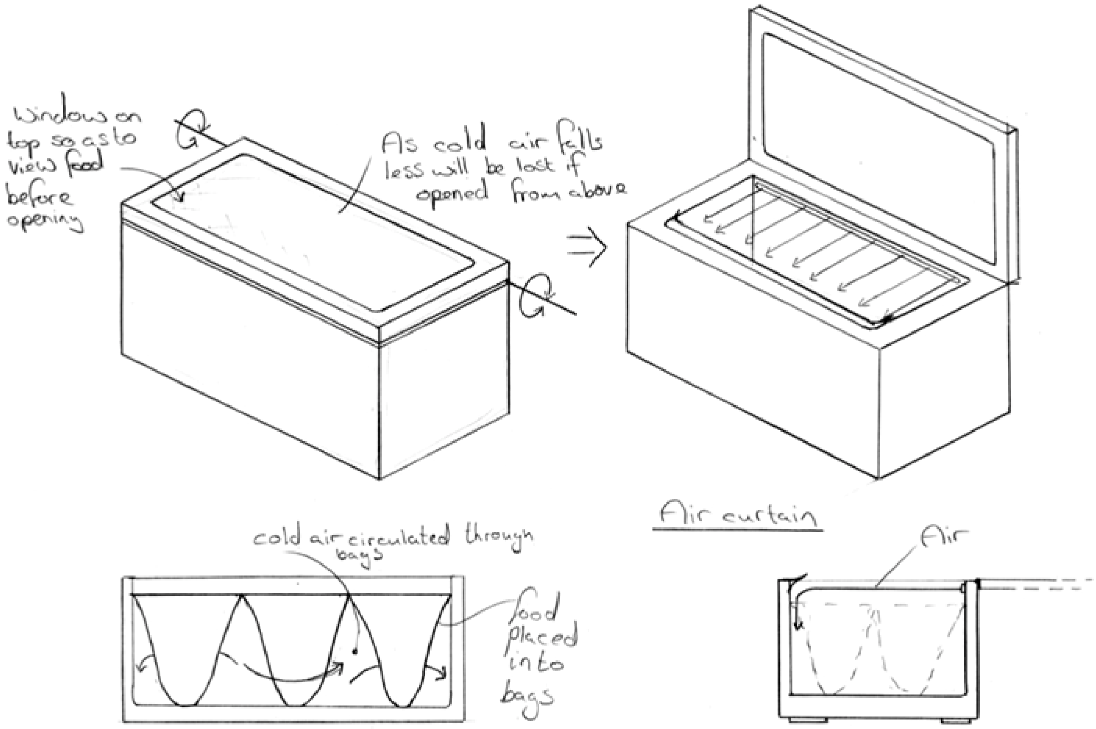
3. Multi-Section



4. Tilt Access



5. Chest Bags



6. Glass Door

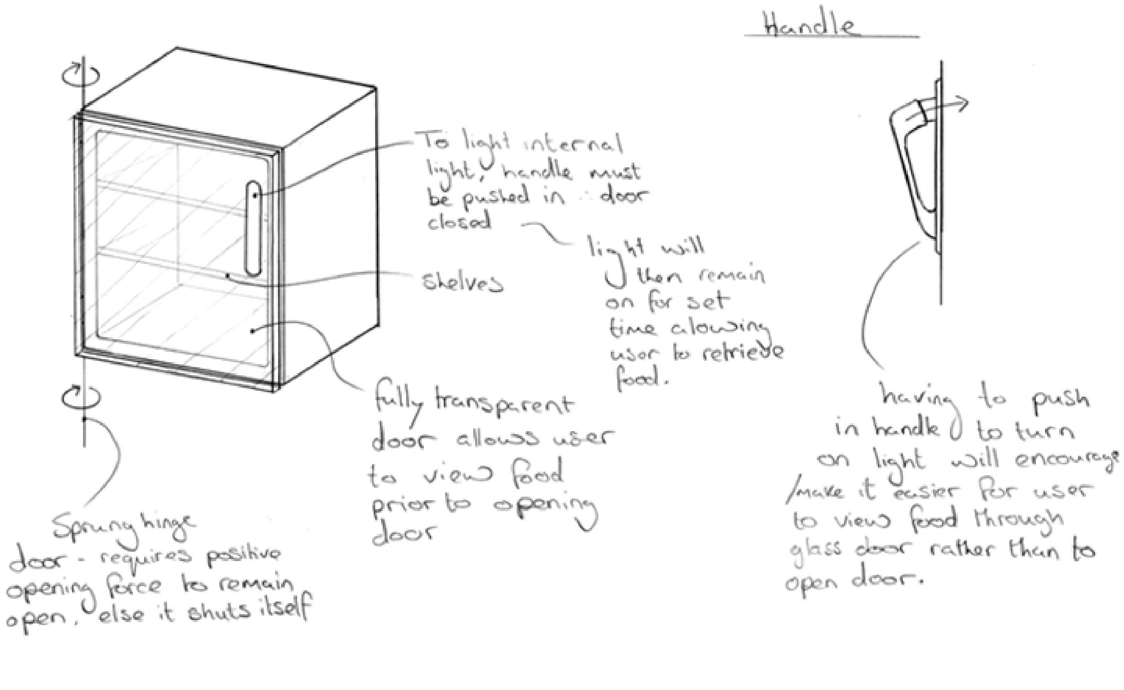
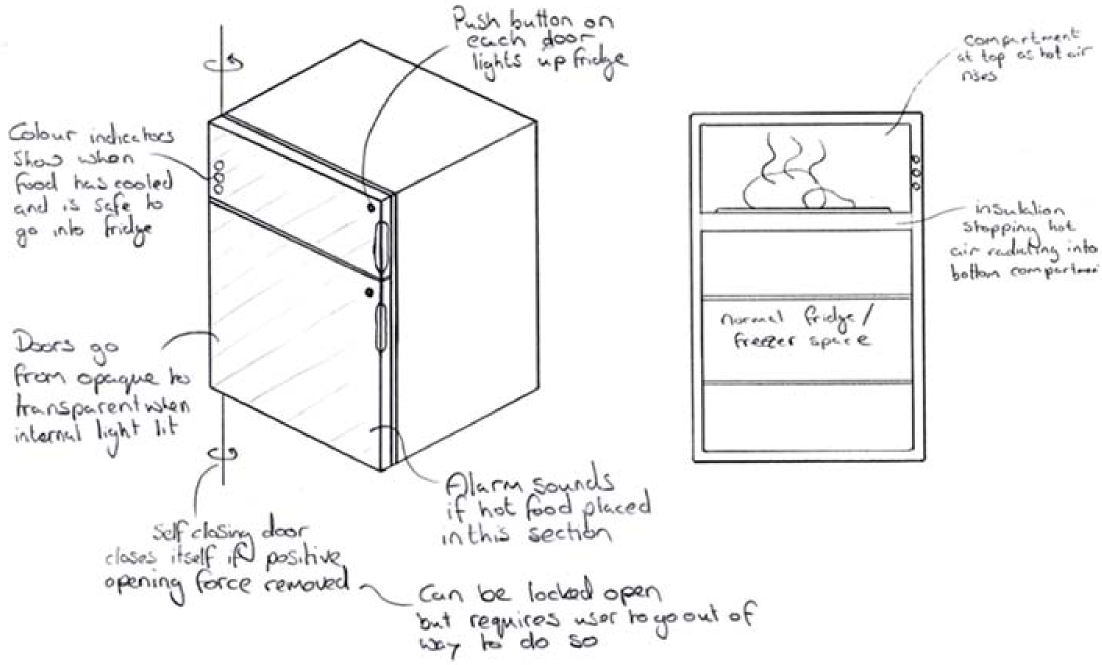
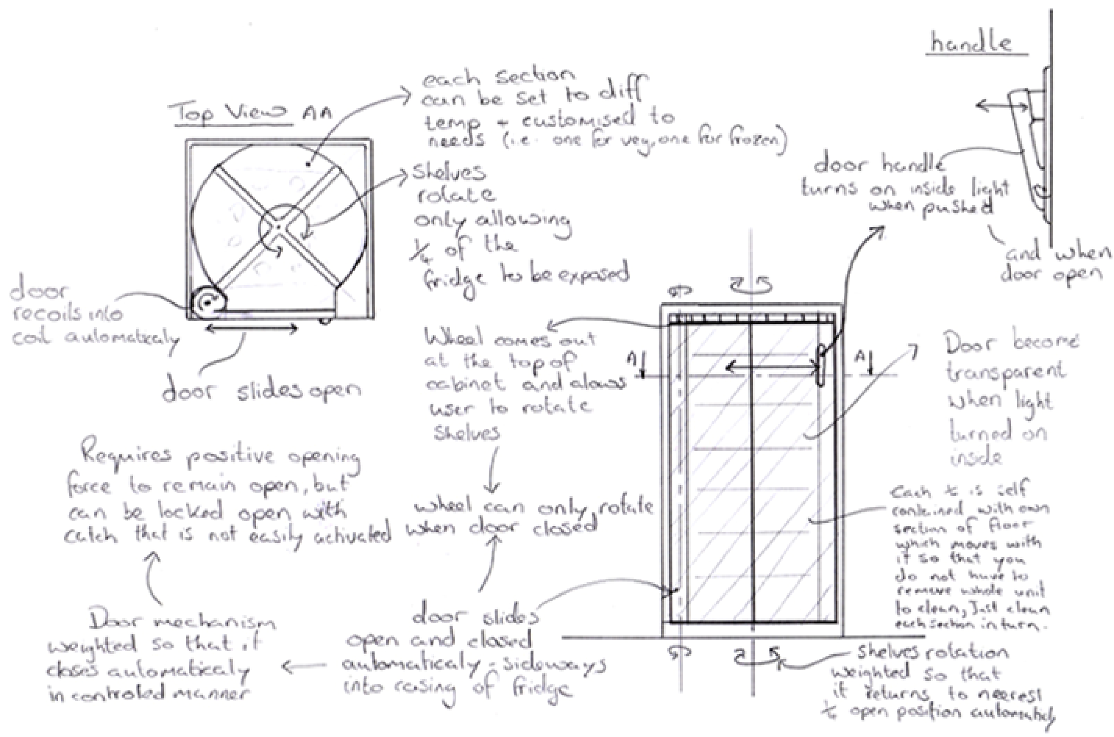


Figure 52 - Enlarged - Six revised design concepts for a User-Efficient refrigerator

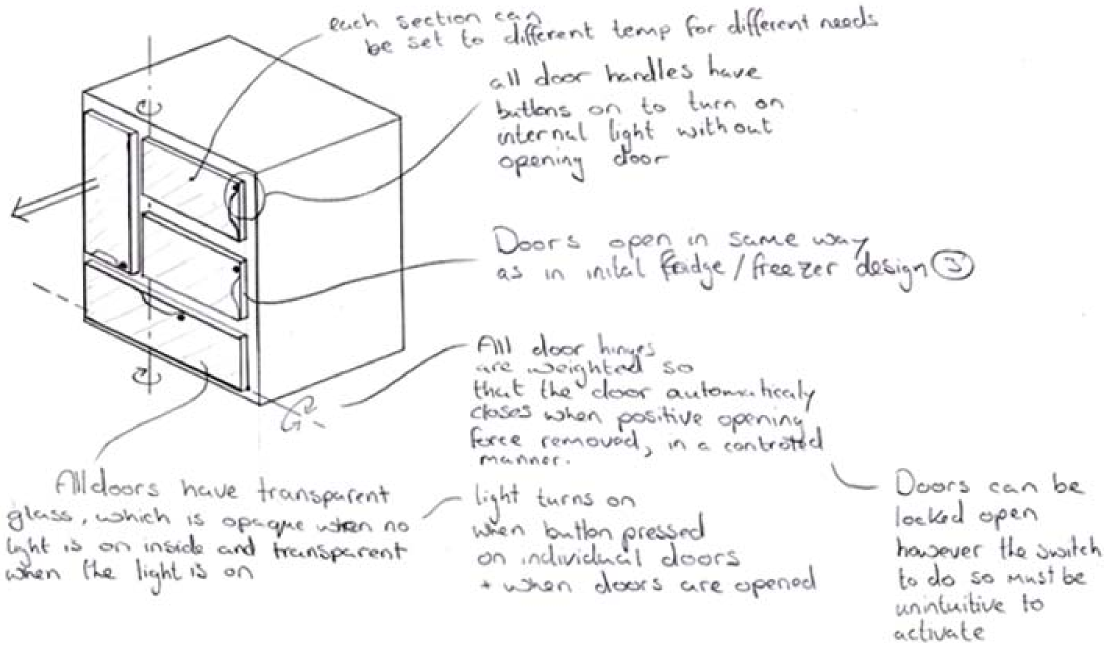
1. Glass Door Cooling Section



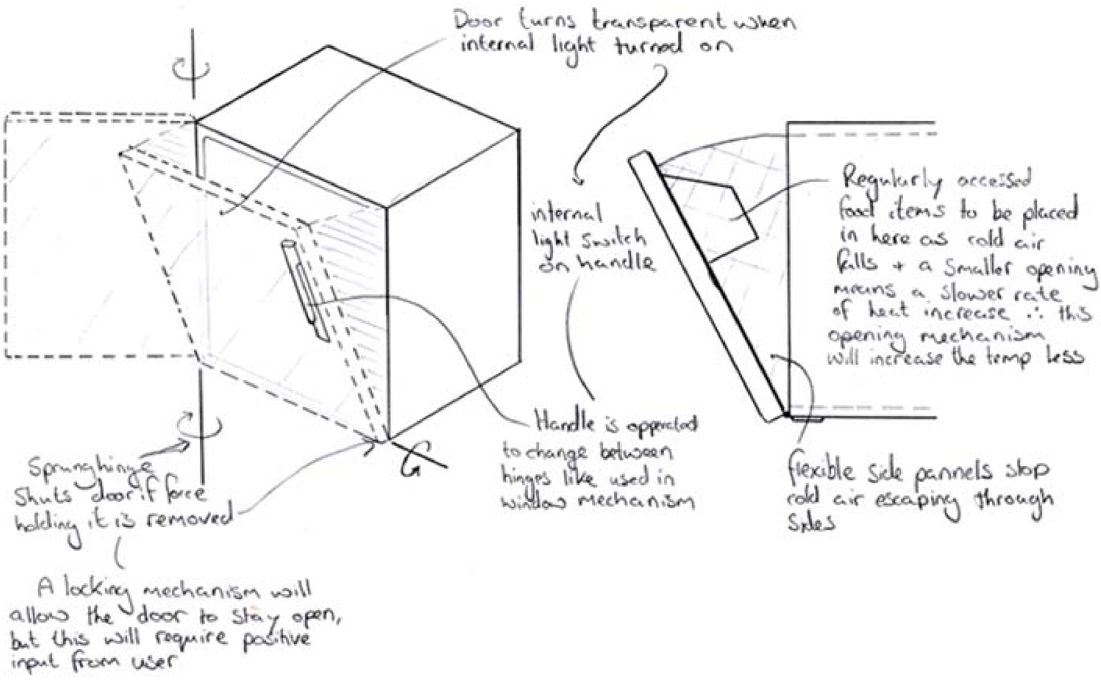
2. Glass Door Rotating Carousel



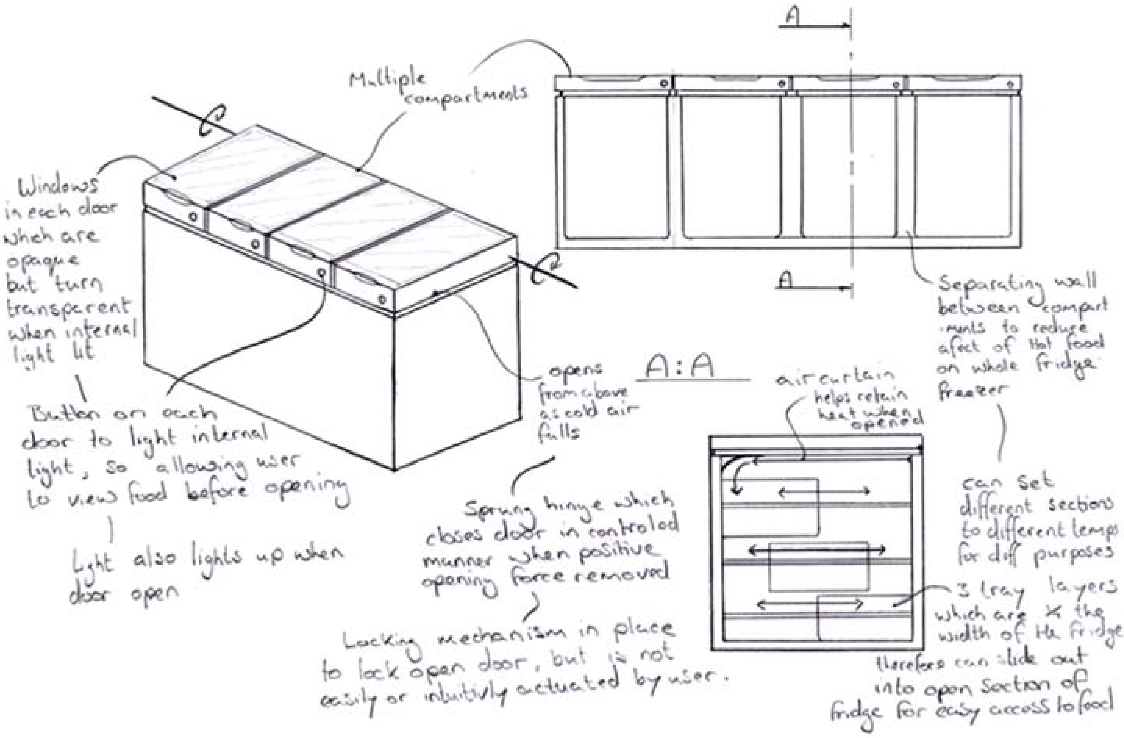
3. Glass Door Multi-Section



4. Glass Door Tilt Access



5. Glass Door Multi-Section Chest



6. Glass Door Multi-Section

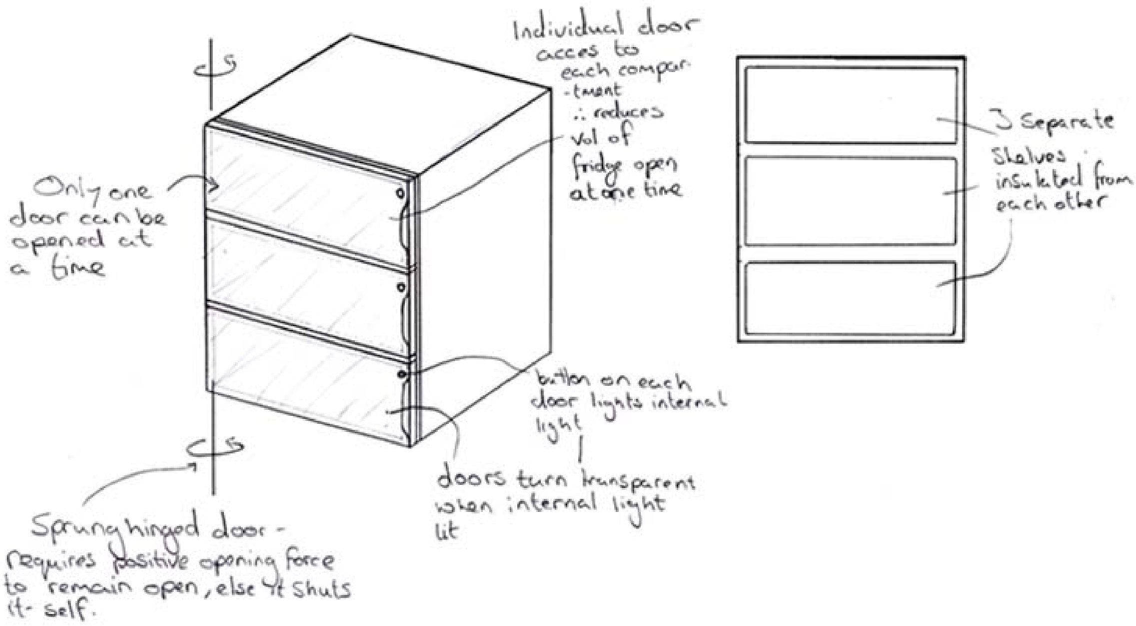
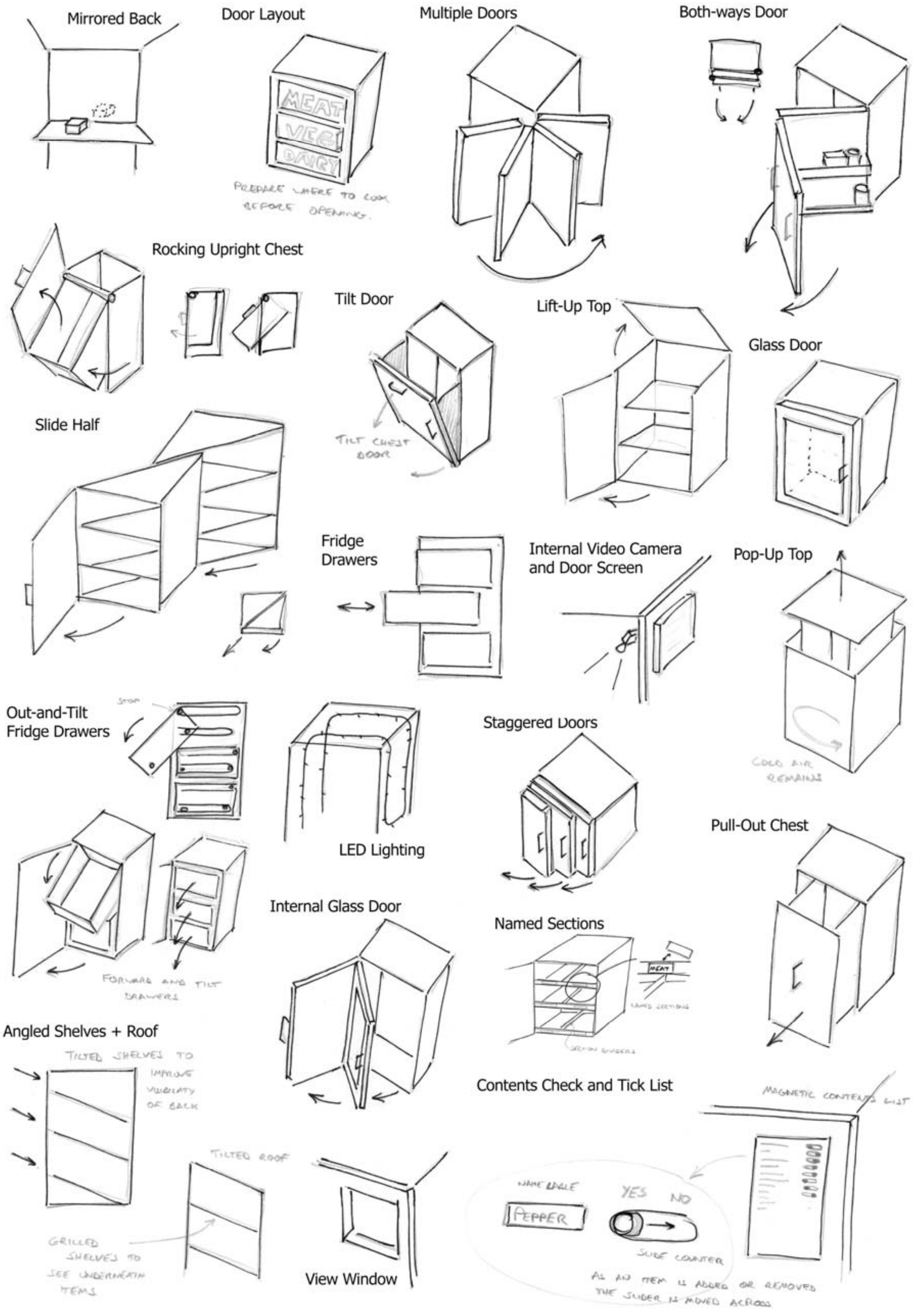
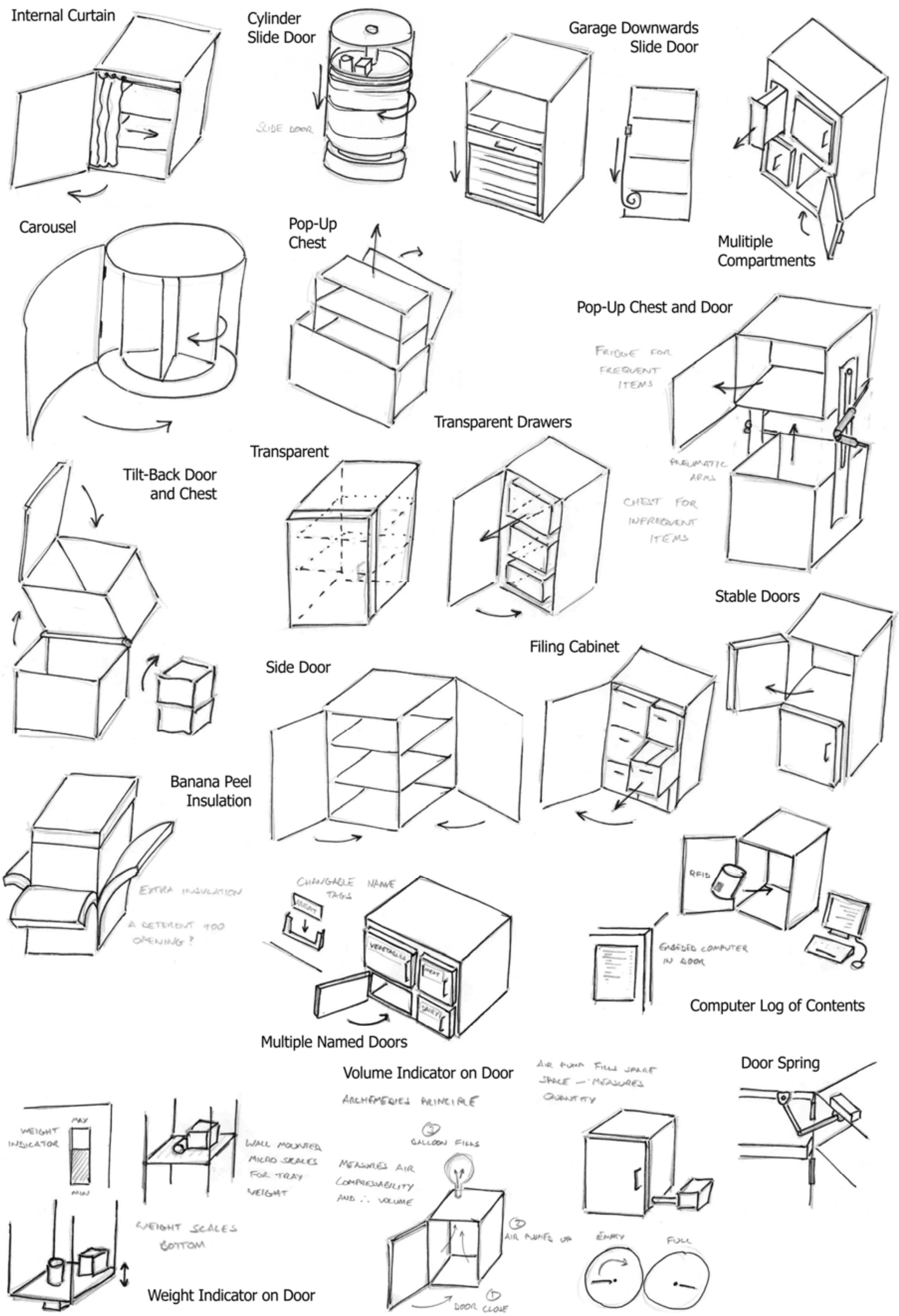


Figure 53 - Enlarged - 50 Refrigerator Product Features




Internal Curtain
Cylinder Slide Door
SLIDE DOOR
Garage Downwards Slide Door
Mulitiple Compartments
Carousel
Pop-Up Chest
Pop-Up Chest and Door
FRIDGE FOR FREQUENT ITEMS
PNEUMATIC ARMS
CHEST FOR INFREQUENT ITEMS
Transparent Drawers
Transparent
Tilt-Back Door and Chest
Stable Doors
Filing Cabinet
Side Door
Banana Peel Insulation
EXTRA INSULATION
A DETERENT TOO OPENING?
CHANGABLE NAME TAGS
MEAT
VEGETABLES
DAIRY
RFID
EMBEDED COMPUTER IN DOOR
Computer Log of Contents
Multiple Named Doors
Volume Indicator on Door
ARCHEMEDIES PRINCIPLE
AIR PUMP FILLS SPARE SPACE – MEASURES QUANTITY
Door Spring
WEIGHT INDICATOR
MAX
MIN
WALL MOUNTED MICRO SCALES FOR TRAY WEIGHT
WEIGHT SCALES BOTTOM
Weight Indicator on Door
② BALLOON FILLS
MEASURES AIR COMPRESSABILITY AND ∴ VOLUME
③ AIR PUMPED UP
① DOOR CLOSE
EMPTY
FULL

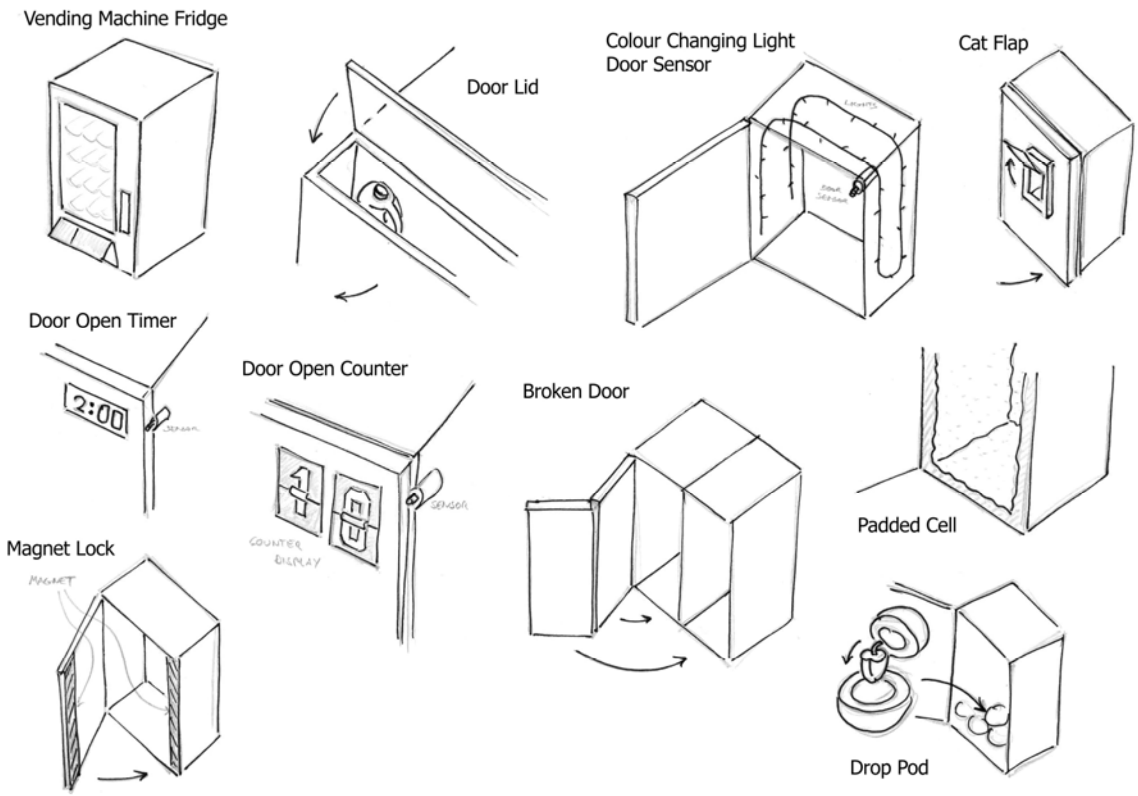
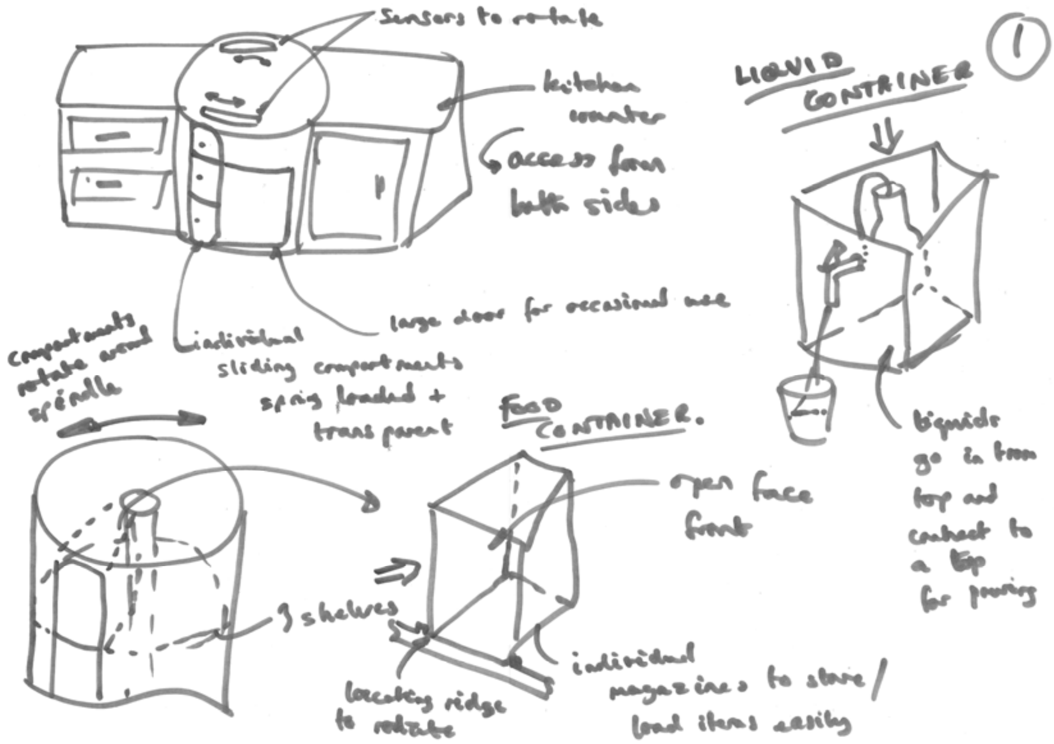

Vending Machine Fridge
Door Lid
Colour Changing Light
Door Sensor
Cat Flap
Door Open Timer
2:00
SENSOR
Door Open Counter
SENSOR
COUNTER DISPLAY
Broken Door
Padded Cell
Magnet Lock
MAGNET
Drop Pod

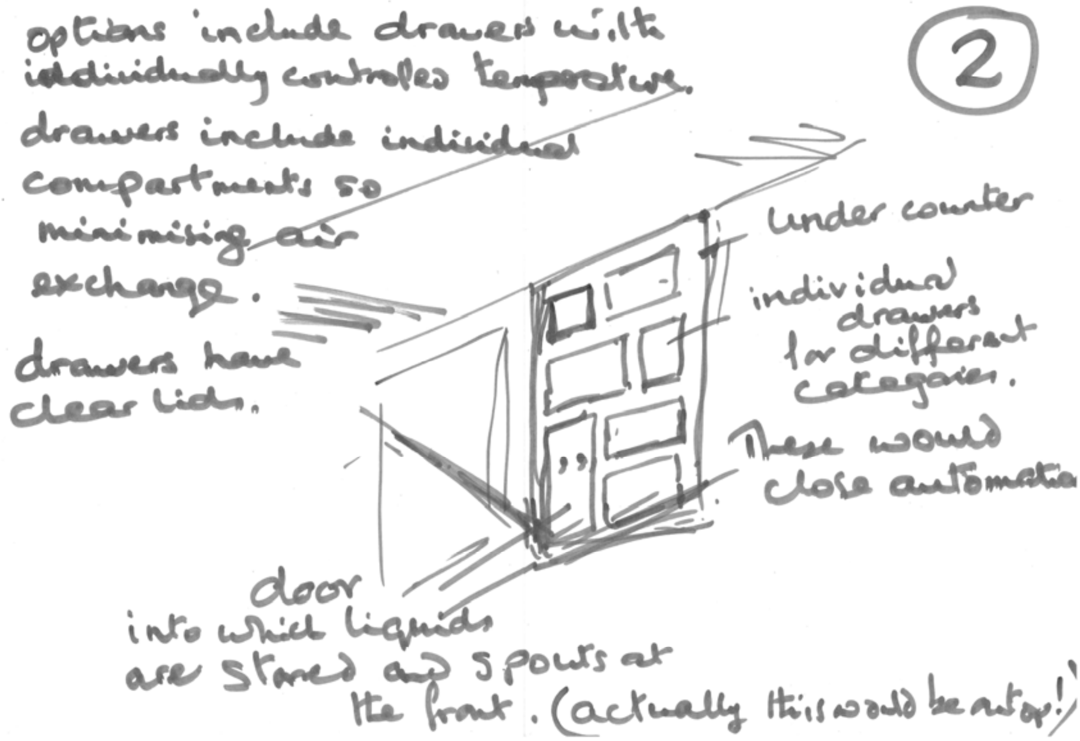
Figure 54 - Enlarged - The final three ideas for all five teams with a summary title and description

Team 1 “Control”

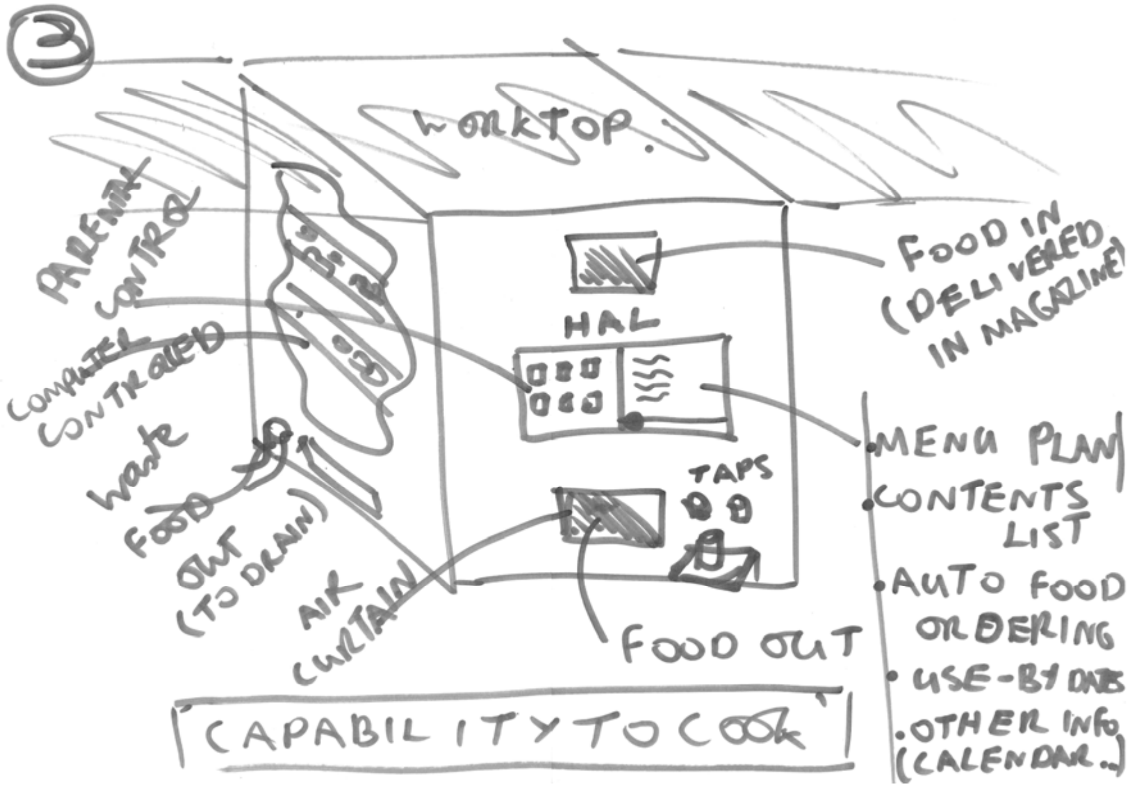
Rotating Carousel + Drink Tap



Multiple Compartments

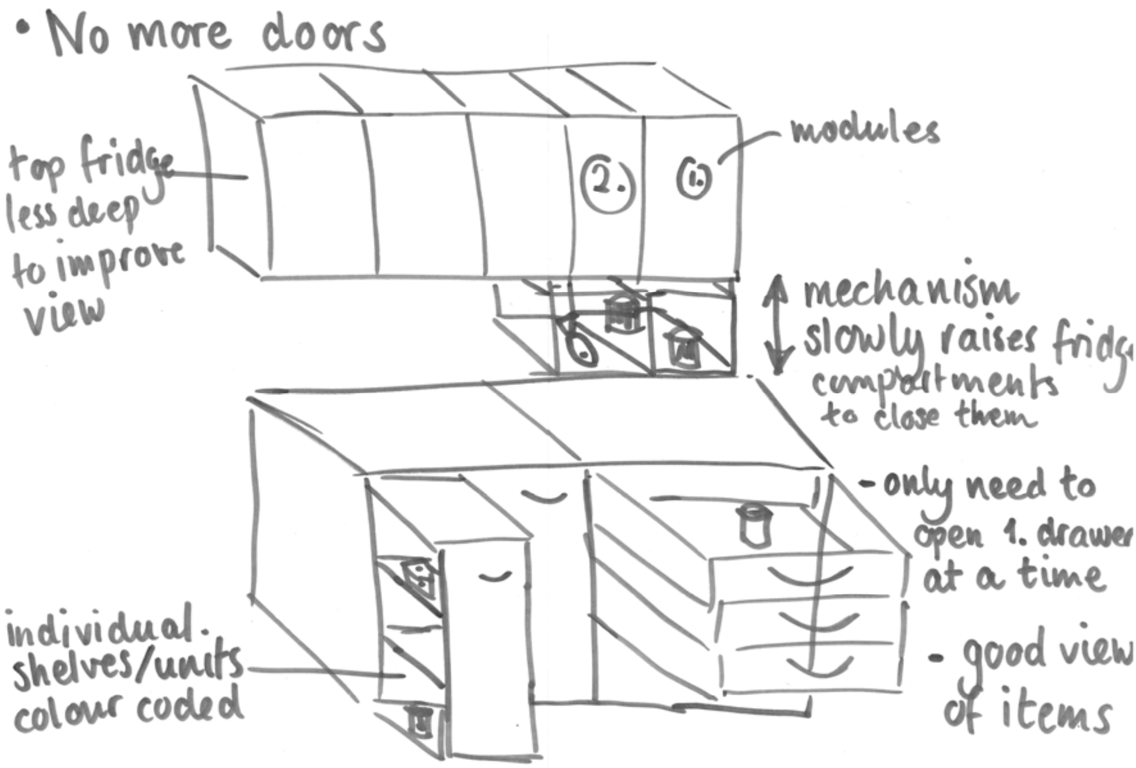


Artificial Intelligence

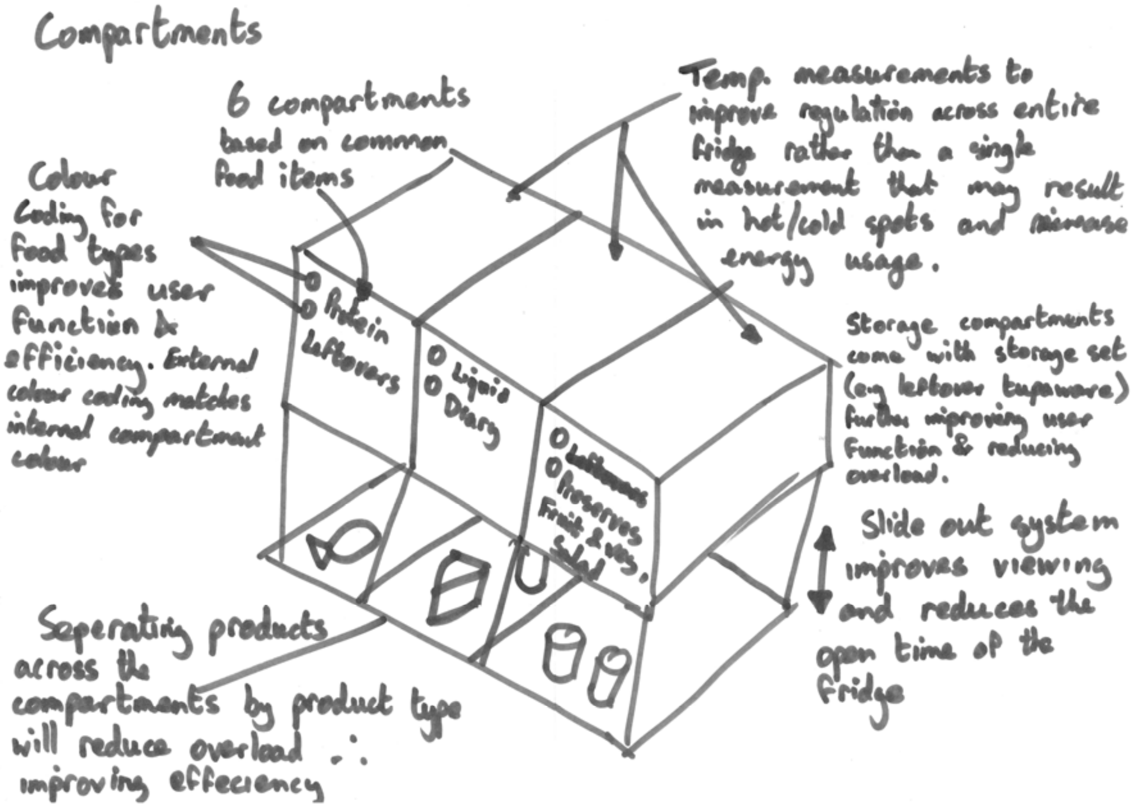


Team 2 "Placebo"

Multiple Compartments



Multiple Compartments



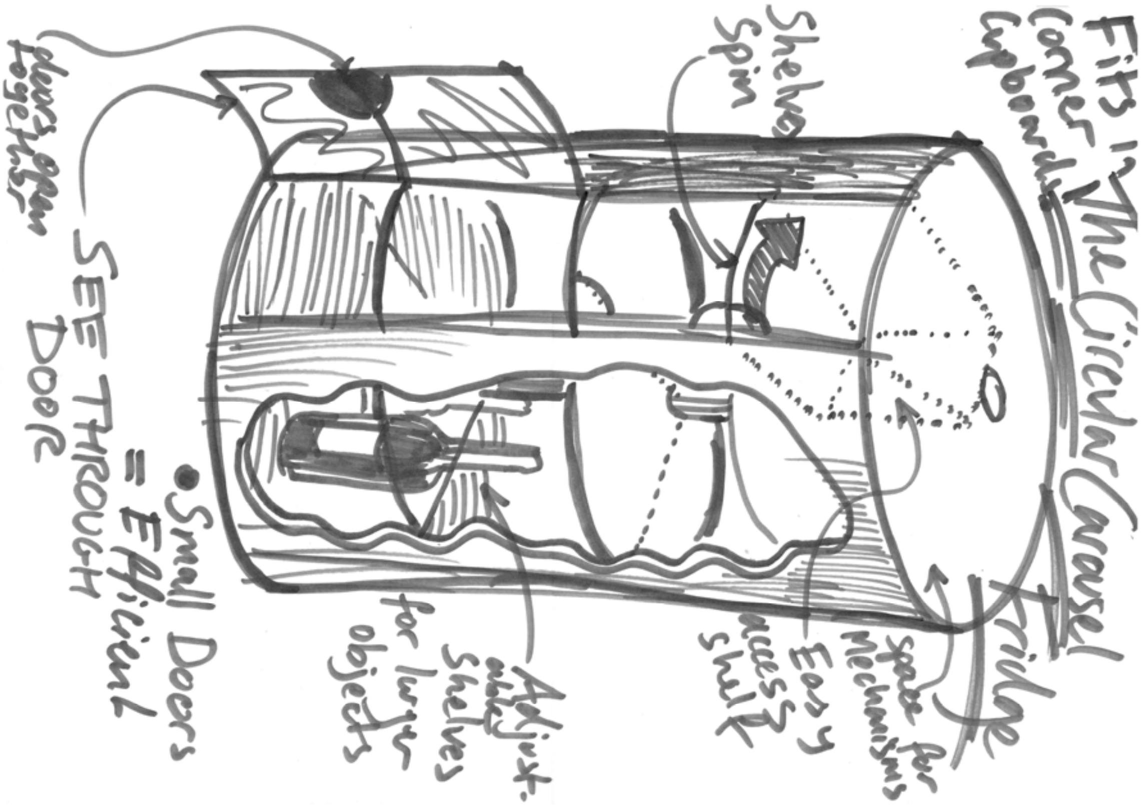
Customisable Display

Customisable features

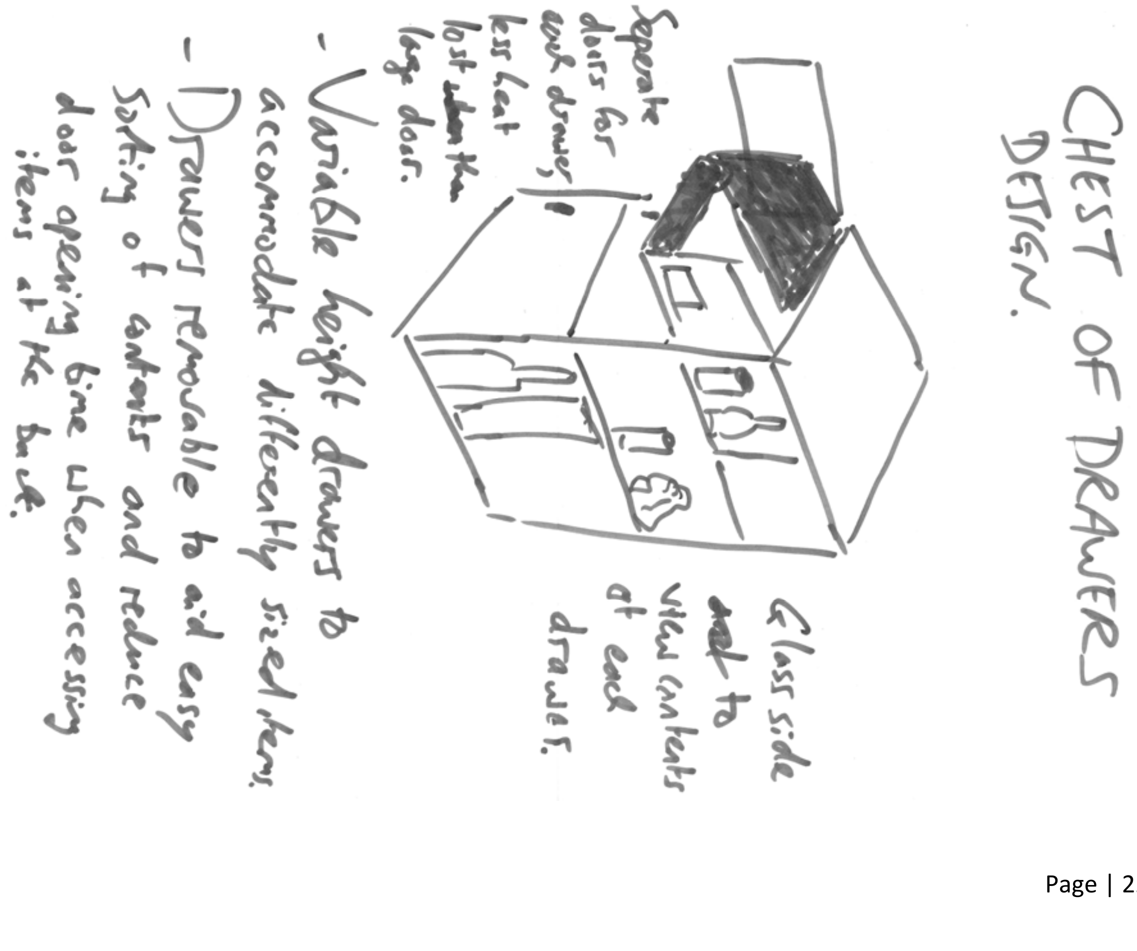
- Customisable sound/voice when compartment is closed
  > Audio 'reward' for efficiency
- changeable labels to define foods in each compartment
  > can be standardised or hand written
- Display showing ave opening time of fridge displays money saved/spent due to energy loss
  > colour indicators for children
- Customisable face plates to fit in with existing kitche appliances/cupboard doors
- Reasonable length reminder if fridge is left open
  >if it has obviously been forgotton/opened by child.

Team 3 "Video"

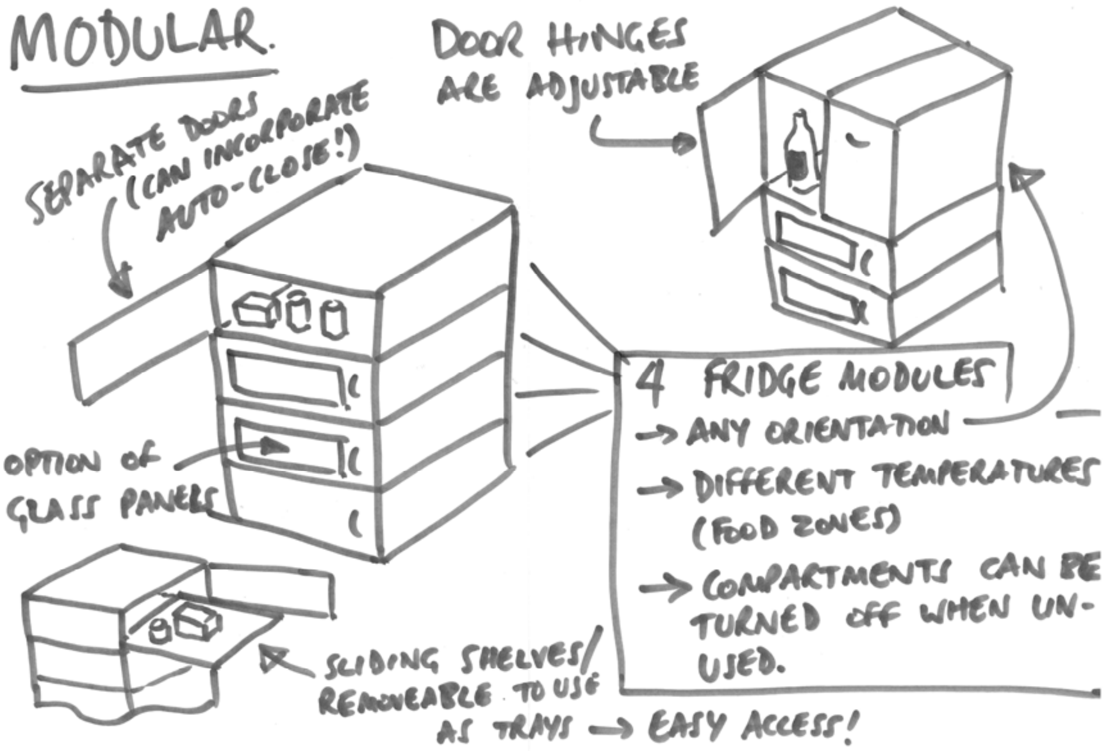
Rotating Carousel



Clear Side + Multiple Doors

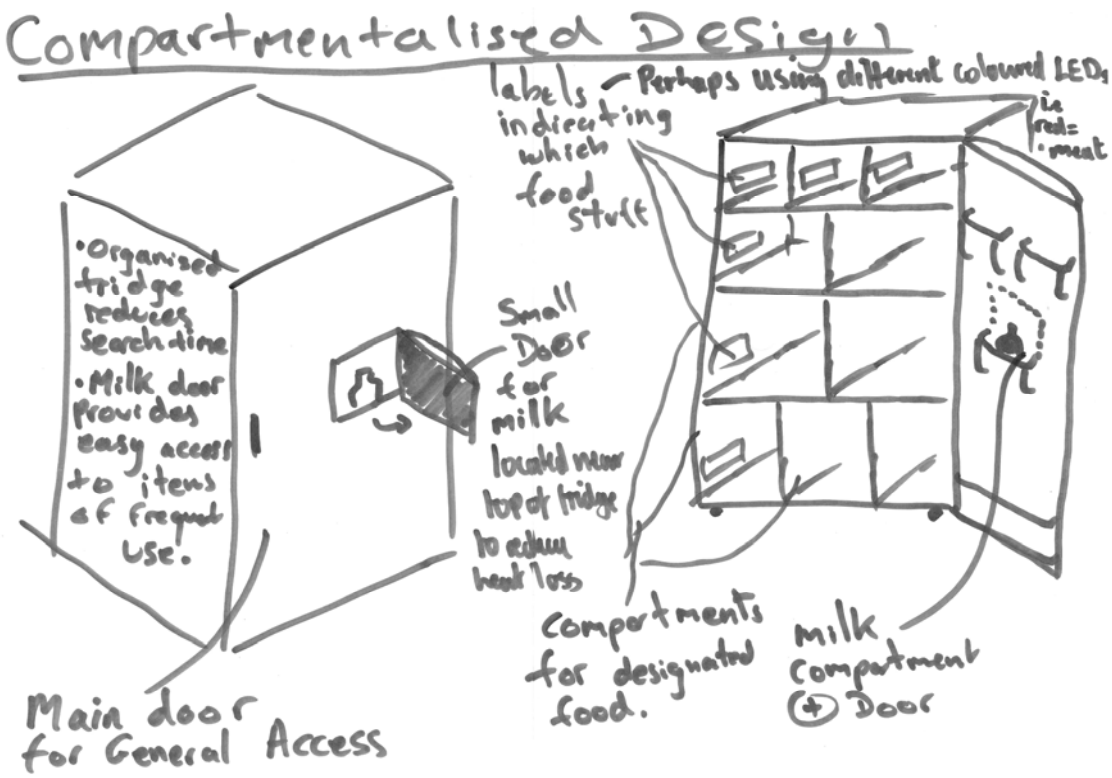


Multiple Compartments

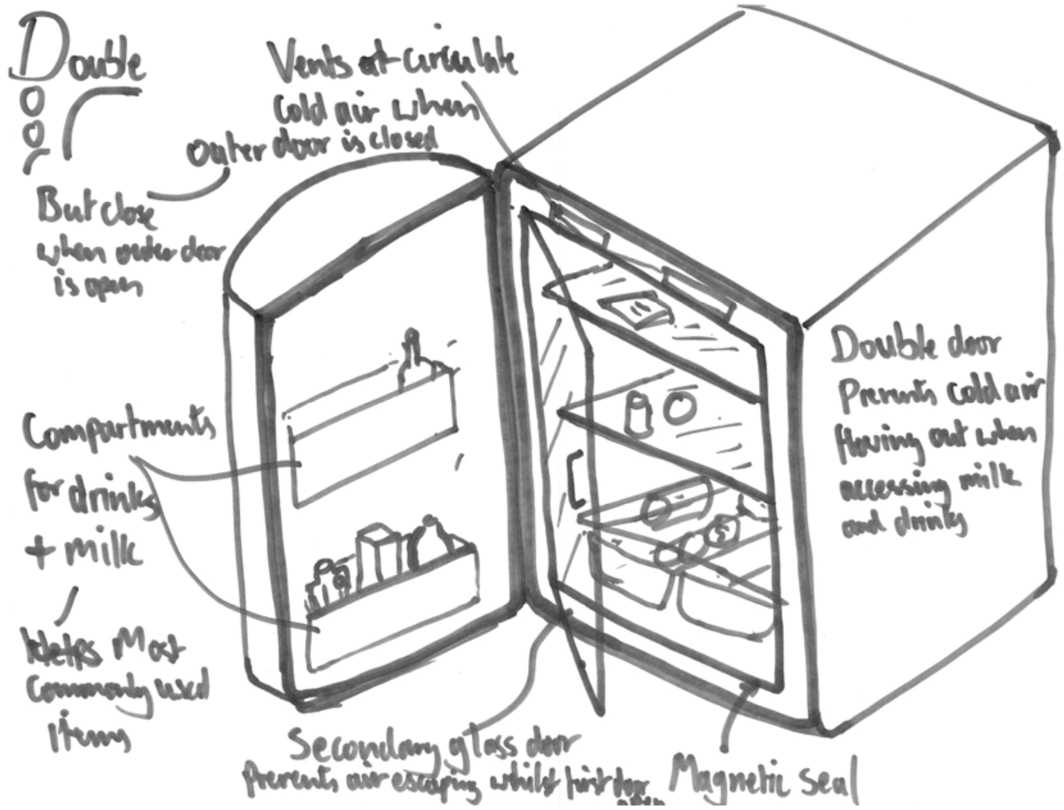


Team 4 “Data”

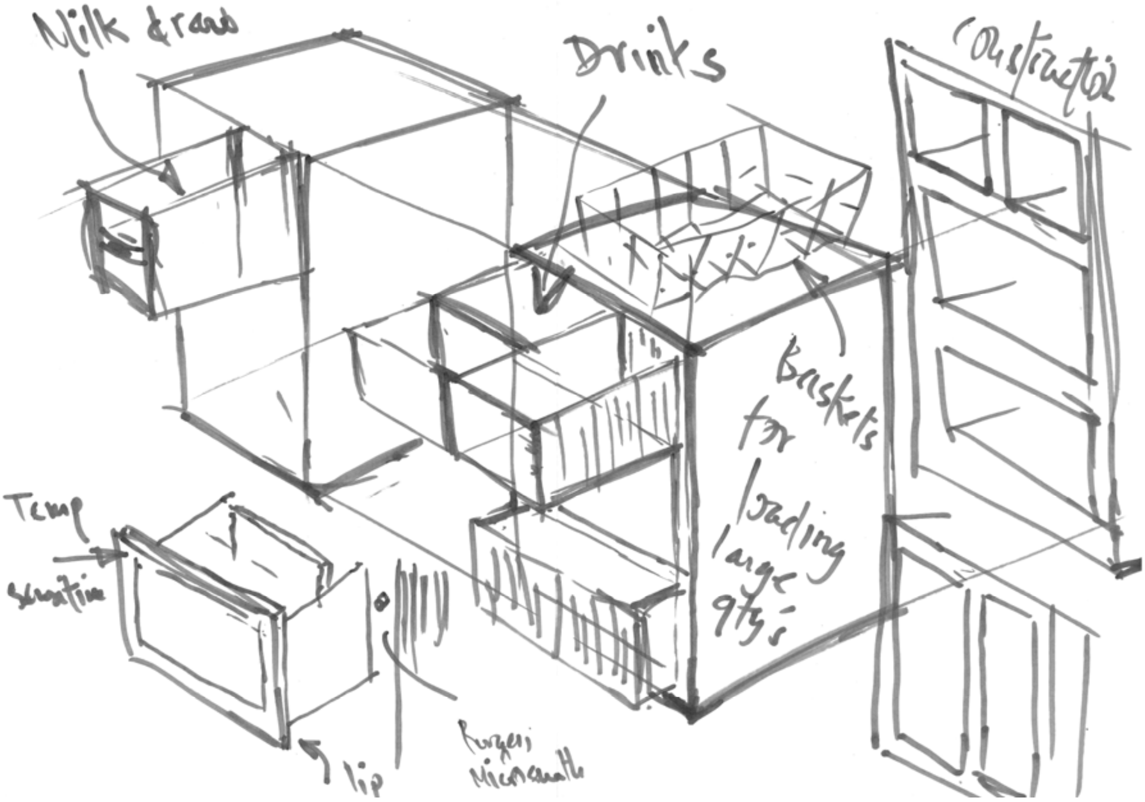
Multiple Sections + Hatch



Internal Clear Door

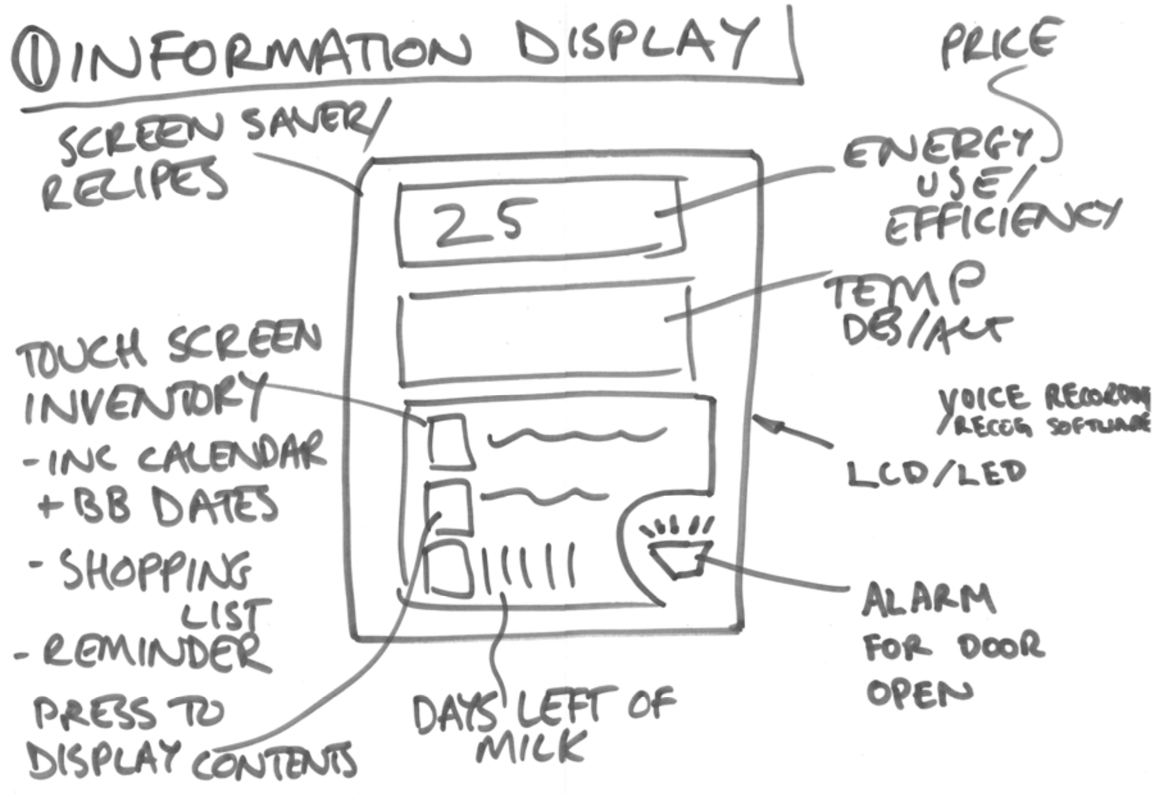


Multiple Compartments

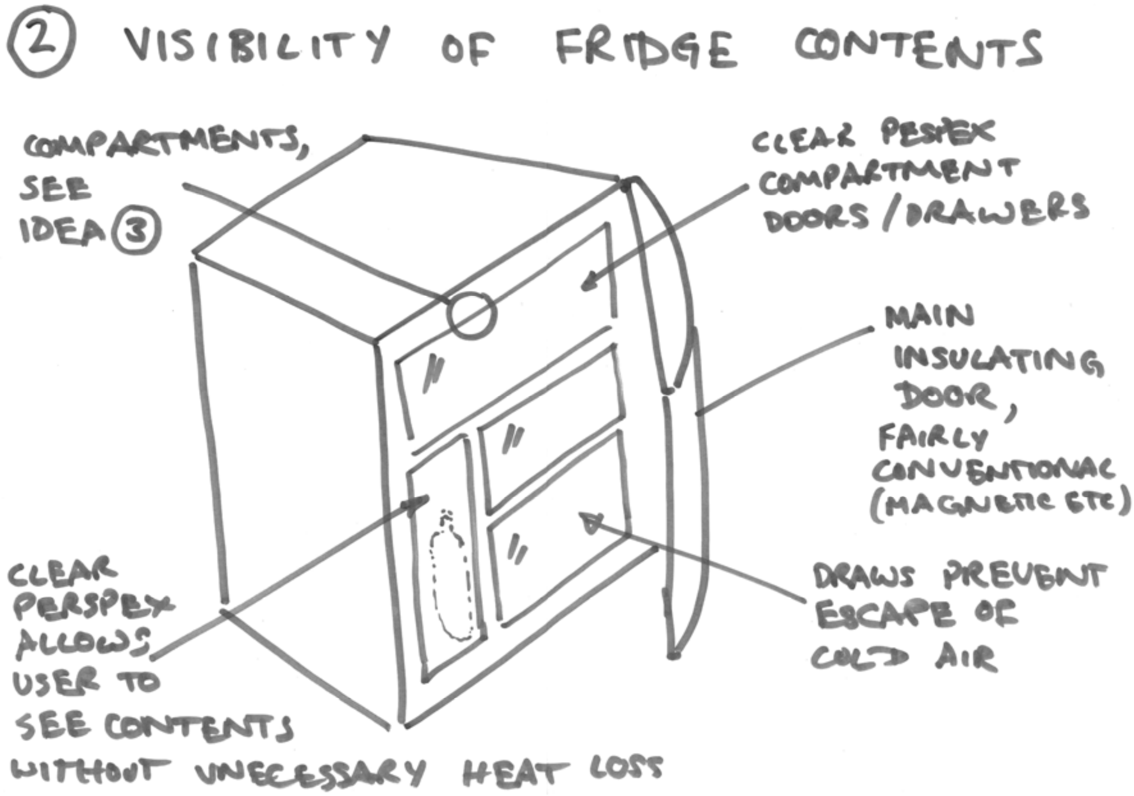


Team 5 "Data + Clips"

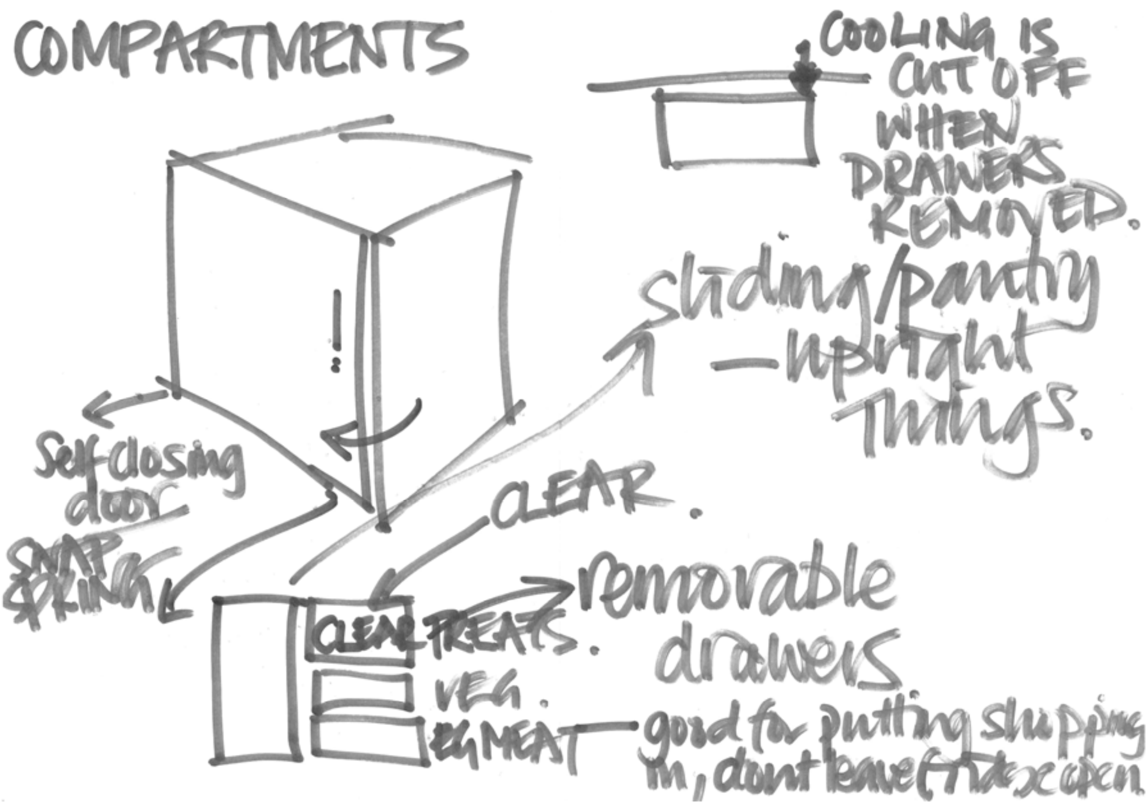
Customisable Display



Internal Clear Compartments



Multiple Compartments


COMPARTMENTS
COOLING IS CUT OFF WHEN DRAWERS REMOVED.
sliding/pantry
- upright things.
Self closing door
SNAP SPRING
CLEAR.
removable drawers
CLEAR
TREATS.
VEG.
EG MEAT
good for putting shopping
in, dont leave

10.0 Publications

10.1 Journal Papers

Elias E.W.A., Dekoninck E.A., and Culley S.J., 2008, Designing for Use-Phase Energy Losses of Products, Proc. IMechE, Part B: J. Engineering Manufacture, 2009, 223(B1), 115 - 120. DOI: 10.1243/09544054JEM1295

Elias E.W.A., Cash P.J., Dekoninck E.A., and Culley S.J., 2011, Insights from a Small Scale Design Experiment: Using Information in Design, Design Studies [Under Review]

Cash P.J., Elias E.W.A., Dekoninck E.A., and Culley S.J., 2011, Insights from a Small Scale Design Experiment: A Rigorous Method and Critique, Design Studies [Under Review]

Cash P.J., Elias E.W.A., Dekoninck E.A., Hicks B.J., and Culley S.J., 2011, A Method for Developing Placebo Controls for Empirical Design Research, Research in Engineering Design [Under Review]

10.2 Conference Papers and Presentations

Elias E.W.A., Dekoninck E.A., and Culley S.J., 2007, The potential for domestic energy savings through assessing user behaviour and changes in design, EcoDesign2007 - 5th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, December 10-13, Tokyo, Japan. **(Best Paper Award)**

Elias E.W.A., Dekoninck E.A., and Culley S.J., 2008, Prioritisation Methodology for User-Centred Design of Energy Using Domestic Products, International Design Conference – Design, May, Dubrovnik, Croatia.

Elias E.W.A., Dekoninck E.A., and Culley S.J., 2008, Assessing User Behaviour for Changes in the Design of Energy Using Domestic Products, IEEE International Symposium on Electronics and the Environment ISEE, May 19-22, San Francisco, California, US. **(Invited Speaker)**

Elias E.W.A., Dekoninck E.A., and Culley S.J., 2009, Quantifying the Energy Impacts of Use: A Product Energy Profile Approach, LCE 2009 the 16th CIRP International Conference on Life-cycle Engineering 4th – 6th May, Egypt, Cairo.

Elias E.W.A., Orme M., Dekoninck E.A., and Culley S.J., 2009, A Morphological Design Approach to User-Efficient Design, International Conference on Engineering Design, ICED, 24th - 27th August, Stanford, California, US.

Elias E.W.A., Chamakiotis P., Howard T.J., Dekoninck E.A., and Culley S.J., 2011, Can a Virtual Design Environment Enhance Group Creativity and the Use of Stimuli?, International Conference on Research Into Design (ICoRD '11), 10th - 12th January, Bangalore, India.

10.3 Other Conference Presentations

Elias E.W.A., Dekoninck E.A., and Culley S.J., 2008, 'Behaviour Driven Design, Designing User Efficient Products', Design Behaviour: Making it Happen, 17th October, University of Loughborough, UK. **(Invited Speaker)**

Elias E.W.A. and Dekoninck E.A., 2010, Design for Efficiency - Consumer Products in the Kitchen, Materials Technologies for Energy Applications - A UK Showcase, 1st - 5th March, Manchester, UK. **(Invited Speaker)**

10.4 Research Posters

Elias E.W.A., 2008, Research Poster, Engineering Design Research Summer School 2008, Design Society, Ilmaneu, Germany. **(Best Poster Award)**

Elias E.W.A., 2009, Research Poster, International Conference of Engineering Design ICED, Special Interest Group in Eco-Design, Stanford University, California. **(Active Participant)**

10.5 Other Publications

Dekoninck E.A., Elias E.W.A., (Awaiting publication). 'Eco-design: the evolution of dishwasher design and the potential for a more user-centred approach'. Handbook of Human Factors in Consumer Product Design - Part 3: case-studies. Taylor & Francis Group. ed. NA. Stanton.

Elias E.W.A., Dekoninck E.A., and Culley S.J., 2008, Assessing User Behaviour for Changes in the Design of Energy Using Domestic Products' Article in the Institute of Engineering Design Magazine, [adapted from the researcher's conference paper of the same name]

Elias E.W.A., 2009, 'User-Efficient Design: Improving the Energy Efficiency of User Behaviour - A Behaviour Design Case Study', A Design Case Study for Industry, University of Bath, UK.

Elias E.W.A., 2010, 'User-Efficient Design: Improving the Energy Efficiency of User Behaviour - Prototype Refrigerator Results', A Design Case Study for Industry, University of Bath, UK.

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